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Títol PFC:

STUDY OF MESH DEFORMATION FEATURES OF AN OPEN SOURCE CFD PACKAGE AND APPLICATION TO A GEAR PUMP SIMULATION

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Summary: A study of the mesh deformation capabilities of an open source Computational Fluid Dynamics (CFD) package is presented in this document. First, previous works on the matter are explained, and an introduction to dynamic meshes and a description of OpenFOAM, the chosen CFD package, are presented. Second, the steps needed to perform the two-dimensional simulation of an oil gear pump are developed in detail. Those steps include meshing the geometry, moving the mesh and finally solving the flow. The final part of this study includes the results and some conclusions, and possible future and derived works are listed. At the end of the document the budget of the study, environmental concerns and the bibliography and references are presented.

Table of Contents

List of Figures

List of Tables

1 PURPOSE

The purpose of this study is to gather, acquire and generate knowledge about the capabilities of an open source Computational Fluid Dynamics (CFD) package, named OpenFOAM, regarding dynamic mesh handling.

The study is focused around the application of these dynamic mesh features to develop a two-dimensional simulation of an oil gear pump.

2 JUSTIFICATION

The complex problems that engineers face nowadays in the field of fluid dynamics are studied and solved by means of CFD. The more complex the geometry, its movement, or the flow are, the more computational power is needed to perform an adequate simulation, not only in terms of accuracy, but in terms of time too.

This computational power is usually deployed in terms of parallel processing. Problems are decomposed in parts that are calculated by separate processors, which keep communicating between them during the calculations. Then, once the solution is obtained, all parts of it are merged again.

However, commercial CFD software licenses are very expensive and, in order to run the software on multiple processors at the same time, one must acquire a license for each processor in which the simulation is going to run. Additionally, licenses must be renewed on a yearly basis, which may render the costs even more prohibitive.

On the other hand, some open source alternatives exist. Open source software is completely free of charge, and it can be run on as many processors as the user needs. In addition to that, the user can examine and modify the source code, if needed. In comparison, commercial software acts as a black box, one can't be certain of what is being calculated.

But open source software has its cons too. It sometimes lacks the amount of documentation and professional support that commercial software has, or it is offered as a separate product for a certain price. However, a helpful community has formed around it. The users are many times required to experiment with the software and ask other users about any problems they might face, and they are encouraged to share their experiences with others so that the global community knowledge is constantly growing.

This study fits into this philosophy, as its main target is to generate a knowledge, a know-how, that others may be able to exploit in a future work. As such, this work is developed so that other users can easily follow the steps here presented for their own works.

3 SCOPE

The scope of this study comprises:

- ✔ Research of the mesh deformation features in OpenFOAM.
- ✔ Development of a meshing procedure for the gear pump simulation.
- ✔ Development of a mesh deformation case suitable for the gear pump simulation.
- ✔ Performing the gear pump simulation in parallel. The purpose of the simulation is to verify that the dynamic mesh is working correctly, the focus is not on the analysis of the flow variables.

The following requirements MUST be met:

- ✔ The study must be done exclusively with open source software. This ranges from the meshing tools and CFD package to the operative system and the text processor.

4 INTRODUCTION

4.1 Previous Works

The study presented in this document originated as a continuation of two other works by David del Campo Sud [1] and by José Plácido Parra Viol [2].

4.1.1 Analysis of External Gear Pumps

The main work this study is derived from is the PhD thesis by David del Campo Sud [1] in which an analysis of external gear pumps is presented. External gear pumps are one of the most common types of pumps for hydraulic fluid power applications.

This kind of pump uses two identical gears rotating against each other. One gear is driven by an engine, and it in turn drives the other gear. The model used for this study has an involute teeth profile, the most commonly used in gears because of their unique properties and advantages. Each gear is supported by a shaft with bearings on both of its sides. The working mechanism can be divided in the following three steps:

1. As the gears come out of mesh, they create expanding volume on the inlet side of the pump. Oil flows into the cavity and is trapped by the teeth as they rotate.
2. Oil travels around the interior of the casing in the pockets between the teeth and the casing.
3. Finally, the meshing of the gears reduces the volume, increases the pressure and forces oil through the outlet port.

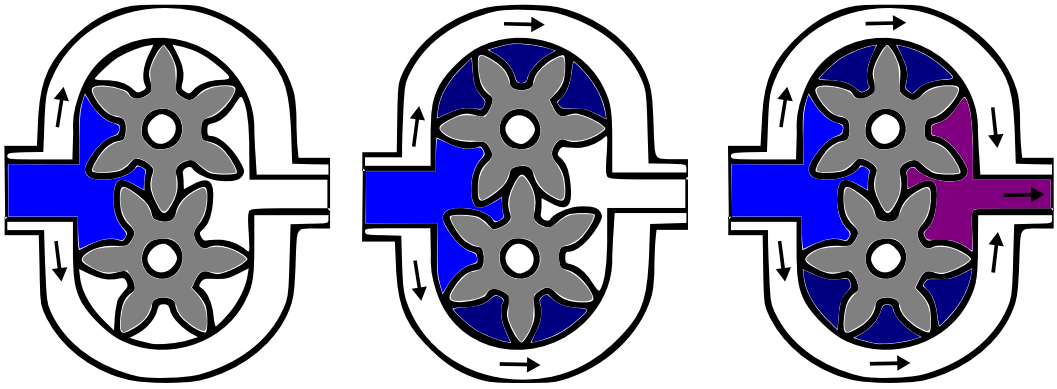


Figure 4.1: Working principle of the external gear pump.

The main purpose of the thesis by David del Campo Sud is to analyze the effect different forms of the suction chamber on cavitation, and the effect of cavitation on the volumetric efficiency. To pursue this target both experimental and numerical analysis were performed.

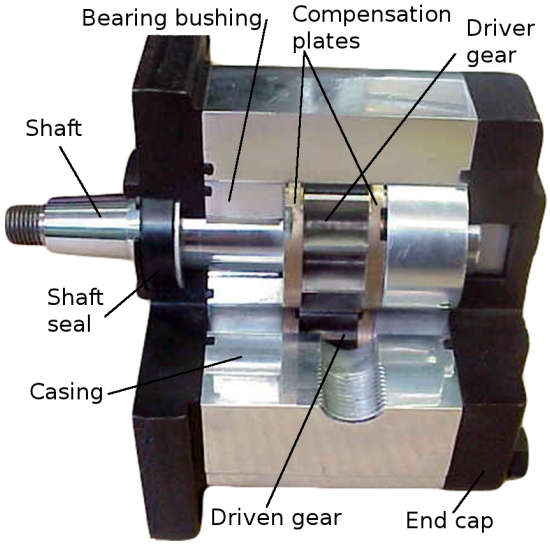


Figure 4.2: Oil gear pump studied by David del Campo Sud in [1].

The flow in the gear pump is inherently three-dimensional, because of the inlet and outlet pipes being circular, the free space in between the gears and the sides of the casing, and rings on the casing to seal the low pressure and high pressure sides for example. But performing a three-dimensional simulation would have been very difficult and taken too long, specially if all of these complexities of the gear pump had been simulated, so two-dimensional simulations were performed, with many simplifications. Although realistic values of the volumetric efficiency cannot be obtained this way, it is possible to compare the effect of cavitation between several two-dimensional simulations, and expect a similar behavior for the real pump.

Simulations included turbulence modeling, cavitation modeling and a contact point simulation between both gears that exists in the real pumps but can't be included in the mesh. These simulations were done with ANSYS Fluent. Because of the licensing requirements simulations had to be performed in serial, which made compulsory all the simplifications that were carried out. If a simulation was to include some or most of the complex effects presented, parallel simulation should be implemented, since the time required to perform the simulations would dramatically increase.

It is because of this that the need to switch to open source software surged, with which the ability to perform parallel simulations comes with no licensing costs.

4.1.2 Initial Study of Mesh Deformation with OpenFOAM

The first study for porting the work done by David del Campo Sud in [1] was started by José Plácido Parra Viol in [2] in his final project. In short, in that study the dynamic mesh solver is studied, a first implementation of the boundary conditions for rotating objects is developed, and it is tested with a simple geometry, like the one depicted in Figure 5.20 in this work.

Although the step forward done in that study was important, and some results of that work are used here, the geometry used by José Plácido Parra Viol was so basic that it could be easily meshed. It is because of this that most of the development presented in the next section of this work is focused towards being able to run the simulation with an arbitrary geometry, in this case the gear pump previously mentioned.

4.2 Dynamic Mesh

The handling of dynamic meshes is required in many simulations in which the domain changes over time. This change can either be prescribed, such as with the gear pump, where the gears rotate driven by an engine; or it can be dependent on the solution of the flow, such as with aeroelasticiy simulations or any other kind of simulation where a structure interacts with the fluid.

In the case of prescribed motion, like the one that is under study in this work, since the movement is known beforehand, a sequence of meshes can be generated, so that they are able to easily accommodate the motion of the boundaries. In between those generated meshes the mesh can be deformed according to the prescribed boundary movement. It is when the deformation of the mesh is excessive that the deformed mesh can be replaced with a new generated one.

But the motion is prescribed at the boundaries, not at the entire mesh. The motion of each point and cell in the mesh needs to be calculated so that the mesh adapts softly to the domain changes. Automatic mesh motion must determine the position of those points based on the prescribed motion of the boundary [6].

This is in fact a whole additional problem, that is added to the problem of solving the flow. That is, boundary conditions for a property (the movement of the points) are defined for a closed domain in which the solution for that property is to be found. Thus the need for a mesh motion equation that has to be solved to find that solution for the movement.

But this equation does not describe a real physical movement, it can be somehow arbitrarily chosen so that it fits the purpose of the dynamic mesh handling adequately. Initial studies trended to considerate the mesh like a solid, for which the deformation was calculated with the finite volume method. Or also the so called spring analogy, which considered the connection between each pair of points as a spring or a one-dimensional bar with a known, prescribed stiffness.

But these methods didn't worked as expected. For the finite volume method the solution of the mesh motion was being obtained in the center of the cells, so the motion of the points had to be interpolated, reducing the quality of the solution. As for the spring analogy, although initially this method yields a linear set of equations, its bad behavior forced the introduction of non-linearities that made the solution of the movement of the mesh too computationally expensive to be used, sometimes even more complex than that of the flow itself [2].

Nowadays, the use of a finite element method based on solving the Laplacian equation for the velocity of the mesh points, $\nabla \cdot (k \nabla \mathbf{u}) = 0$, either with a constant or variable diffusivity *k*, is very extended. The added diffusivity acts as a control for the mesh deformation and quality.

Additionally, it must be noted that the fluid equations that are going to be used to solve the flow must be written for time-changing domains, instead of a stationary one, for the conservation laws to be fulfilled.

Also, if mesh deformation is large or for some special uses, it could be interesting to apply topological changes. These consist on changing the mesh with little or no deformation, by making a part of the mesh move with respect to another one, for instance, or by removing or adding a boundary, for example to simulate the opening and closing of a valve inside a pipe. These methods are not under study in this work, but they must be considered if these changes are adequate for the problem to be solved.

4.3 OpenFOAM Description

OpenFOAM (the name stands for Open Field Operation and Manipulation) is a free, open source CFD software package. It has a large user base across most areas of engineering and science, as OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to solid dynamics, electromagnetics and finances [4].

Its solvers range from incompressible and compressible flows, multiphase flows, combustion, buoyancy-driven flows, heat transfer, particle methods and also solid dynamics and electromagnetics, while providing an extended library functionality with turbulence models, transport and rheology models, thermophysical models, lagrangian particle tracking, and chemical reaction kinetics directly available from its source.

4.3.1 Usage

The pre-processing is done in OpenFOAM by editing the directories and text files that conform a case, as it can be seen in the next section where this study is developed. For instance, for the unfamiliarized reader, the well-known `cavity` tutorial, the first tutorial in the OpenFOAM user guide [3], presents the following file structure:

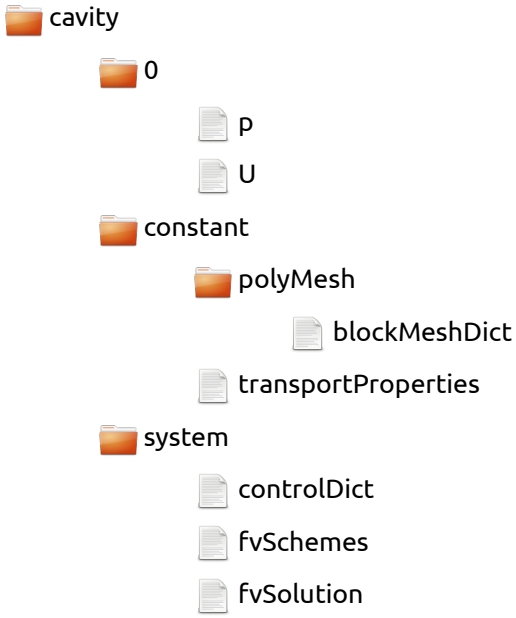


Figure 4.3: File system of the `cavity` tutorial.

The `0` directory represents the first time directory and stores the boundary conditions. Next time steps are saved in subsequent directories, such as `1`, `0.03`, or `5e-05`.

Inside the `constant` directory the properties of the problem that is going to be solved are included, such as the mesh, the properties of the fluid, and other things if required.

The `system` directory contains all the controls of the simulation. Time steps, write precision, etc. are determined in the `controlDict` file, whereas inside the `fvSchemes` file the finite volume discretization schemes are determined for each time derivative, gradient, divergence, laplacian, etc. In the `fvSolution` file the user can select the solver that will calculate each variable. More dictionary files are required if certain OpenFOAM tools are used.

Solvers and other OpenFOAM tools are run directly from the command-line interface, also known as CLI or terminal. Post-processing can be done with the help of an included program called ParaView.

OpenFOAM also counts with some tools to create meshes, from the basic `blockMesh` to the more complex `snappyHexMesh`, and includes many tools for importing meshes created with other software packages. Since it is heavily used in this document, should the reader need it, the `snappyHexMesh` guide in section 5.4 of [3] can be consulted in case of doubt.

4.3.2 Coding

But with no doubt the most important feature of OpenFOAM is the fact that it is open-sourced. While OpenFOAM can be used as a standard simulation package, it offers much more because it is designed to be a flexible, programmable environment for simulation. Equations can be coded in a way much similar to that of its mathematical notation. Take for instance the equation:

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot \rho \mathbf{U}\,\mathbf{U} - \nabla \cdot \mu \nabla \mathbf{U} = -\nabla p$$

In an OpenFOAM solver it can be represented by the code:

```
solve
(
      fvm::ddt(rho, U)
    + fvm::div(phi, U)
    - fvm::laplacian(mu, U)
    ==
    - fvc::grad(p)
);
```

It is because of this that OpenFOAM counts with some advantages with respect to proprietary software, among which the following can be specially remarked:

- Users have total freedom to create their own solvers and libraries, which is typically done by modifying an existing one.
- The solution algorithms are fully transparent, they can be viewed and checked by the user, encouraging better understanding of the physics and equations involved in the problem.

4.3.3 Parallel Execution

Also, OpenFOAM makes running cases in parallel easy. This permits solving more complex problems in less time. Almost everything in OpenFOAM can be run in parallel, and since OpenFOAM is free, compared to the per-processor licenses of commercial software, parallel simulations are much more affordable.

In order to solve a case in parallel the domain is decomposed and each part is allocated to a separate processor. OpenFOAM ships with the OpenMPI library to manage the communications between processors and run parallel applications. OpenFOAM is reported to scale well up to at least 1000 CPUs [4].

For further reference about how OpenFOAM works, the OpenFOAM User Guide [3] and the OpenFOAM Features Guide [4] can be consulted.

4.3.4 Dynamic Mesh Implementation

The most logical implementation of the dynamic mesh in OpenFOAM in order to solve the flow in the gear pump is that suggested by José Plácido Parra Viol in [2]. In short description, the strategy is to generate multiple meshes for multiple positions of the gears during one gearing cycle, so that once the mesh has deformed excessively because of the rotation of the gears, a new mesh can be used.

Then the solver has to be run for multiple gearing cycles to ensure a certain level of convergence, during which the same meshes can be reused multiple times, once per cycle simulated. This implementation is developed in the next section.

5 DEVELOPMENT

5.1 Initial Case Setup

The study presented in this document is focused towards a particular problem, although the developed procedure and its conclusions are of interest for any similar dynamic mesh problem that is going to be solved in OpenFOAM.

In order to start the study, a work directory must be created. In OpenFOAM this is typically accomplished by copying the files of an existing case to a new folder. The existing case must be similar to the one in consideration, this way only a few files need changes to work properly.

A good choice is to look among the tutorials provided with OpenFOAM for a case with similar conditions. Tutorials are sorted by field (incompressible, compressible, electromagnetics, financial, heat transfer, etc.), then by solver. Choosing the solver is an important step in the early beginnings of the work, although it can be changed later. For the gear pump simulation an incompressible solver capable of handling a dynamic mesh is required. The choice is `pimpleDyMFoam`, a modified `pimpleFoam` that handles dynamic meshes. It can do both laminar or turbulent simulations of transient incompressible flow.

The OpenFOAM tutorials are located in the following directory:

```
/opt/openfoamXYZ/tutorials/incompressible/pimpleDyMFoam
```

Where `XYZ` represents the OpenFOAM version. The version of OpenFOAM used in this work is 2.1.0. Inside this directory one finds several tutorials. Two of them, `movingCone` and `wingMotion`. are of interest. The former simulates the known, imposed movement of an object across one axis, a movement similar to the one that is under study. The latter simulates the movement of a two-dimensional airfoil caused by the aerodynamic forces, its mesh being created with `snappyHexMesh`. A similar process will be implemented to mesh the complex geometry this study faces.

Since both tutorials are of interest but none fulfill the scope of the study, the best option is to manually create the new directories, copying the file system and the files from one tutorial or the other as needed. Thus, a directory is created on the desktop, called `gearMain`, inside of which all the other files will be placed.

5.2 Obtaining the Geometry

The geometry for the gear pump was provided in the form of a Gambit MSH file. Gambit is a preprocesing and meshing program in the commercial software Fluent. Since, as required on section 3, all the software used in this study must be open source, the mesh in this file will not be used.

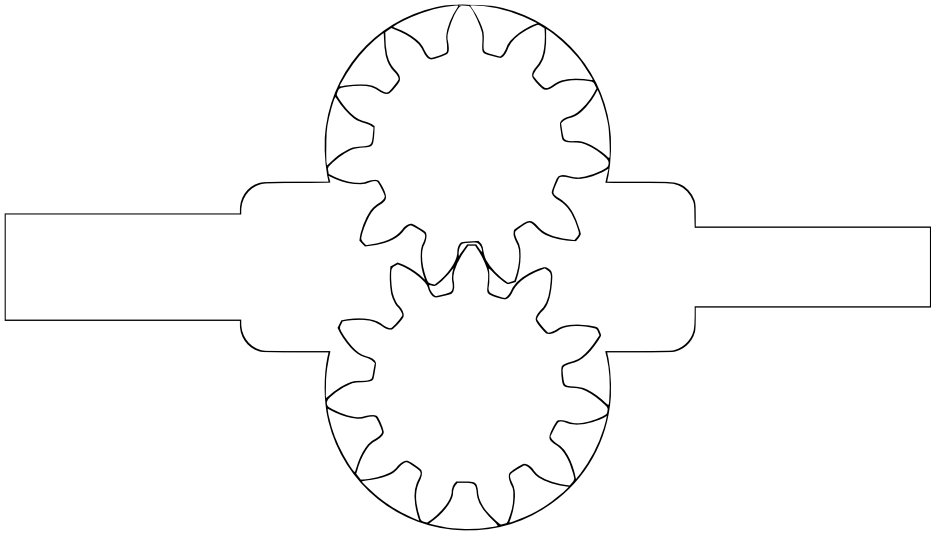


Figure 5.1: Geometry of the gear pump.

The idea is to extract a list of points for the gear and the case of the pump from the file and discard the mesh. In order to do that, the complete mesh must be converted to the OpenFOAM format first, by using the `fluentMeshToFoam` command. This command needs a case directory to be created in order to work, so one is created inside the `gearMain` folder, named `gearFluent`, with the following structure:

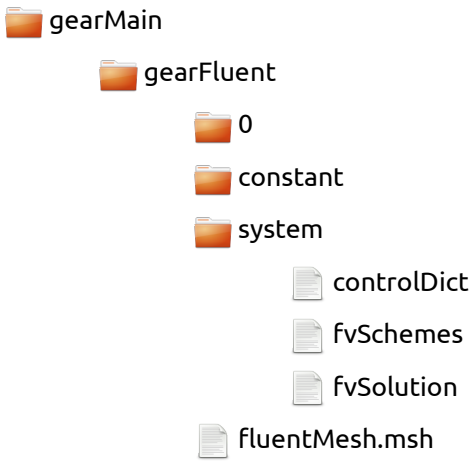


Figure 5.2: File system of the `gearFluent` case.

The `controlDict` , `fvSchemes` and `fvSolution` files can be copied directly from the `wingMotion/wingMotion_snappyHexMesh` tutorial. The user can adjust the write options from the `controlDict` file (`writeFormat`, `writePrecission` and `writeCompression`) as needed, but the default ones should be enough.

Once this case folder is all set the mesh can be converted by opening a terminal, setting `gearFluent` as the working directory and entering the following command:

```
fluentMeshToFoam fluentMesh.msh
```

The mesh will be written inside the `/constant/polyMesh` directory. Once the mesh has been converted it can be opened in ParaView by typing `paraFoam`. Before clicking Apply in the Object Inspector, the patches related to the casing should be selected, and the internal mesh deselected as shown in Figure 5.3.

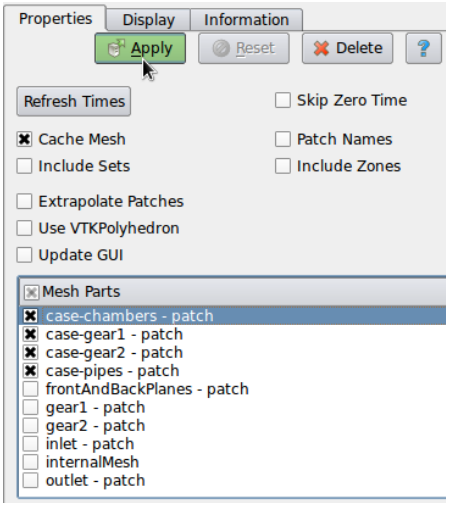


Figure 5.3: Selection of patches in ParaView.

After clicking Apply the data can be exported by going to File, Save Data, and selecting Points as the field association. The points of each case patch are saved in CSV files that can be imported to any spreadsheet program, such as LibreOffice Calc. Each point is written twice, once for a negative z coordinate, and once for a positive z. This can be easily filtered by sorting the rows by the last column, then eliminating the half of the rows with negative z.

Once this has been done, the points of all the CSV files can be merged on a single file, and then copied to a text file, so that all the points of the gear casing are now in a single list, each point in a line, with its x and y coordinates separated with a tab.

This process must be repeated for one of the gears. In this case it is convenient to rotate the points slightly so that a tooth of the gear is pointing directly upwards. This way a single list of points will be valid for both gears, since the number of teeth is odd, and by translating one upwards with respect to the other both will mesh perfectly.

The lower gear is centered on the coordinates origin, so this one will be the reference gear. Again the points are extracted and filtered just as with the casing. To obtain the angle that the points must be rotated, the geometry is inspected in ParaView. One can obtain the coordinates of the center point of the uppermost tooth, and then calculate the angle that the point must be rotated to reach the $x = 0$ plane.

Once all this work is done, the list of points for the casing and for the gear centered at $x,y = 0,0$ has been obtained.

5.3 Generating an STL File

Before being able to mesh the geometry an STL file must be generated. This is because the geometry will be meshed by using `snappyHexMesh`, which takes an STL file as the input. STL files are standardized files that can be handled by many software packages. Inside an STL file multiple solids can be represented as a list of triangles that conform their surfaces. STL files can be written in ASCII or binary format. The ASCII format looks like this:

```
solid name0
      facet normal n1 n2 n3
            outer loop
                  vertex x1 y1 z1
                  vertex x2 y2 z2
                  vertex x3 y3 z3
            endloop
      endfacet
      facet normal ...
      ...
endsolid name0
solid name1
...
```

Such a file can be written easily by hand if the geometry is simple enough, or with the help of a small program if it is more complex. Many CAD softwares can export to this file type too. In this case the most useful option is to write a program to read the point list for the casing and the gear, then apply any desired transformation to the geometry, such as a rotation to the gears, and finally write the geometry as an STL file.

This way it will be easy to automatically generate the geometry for any position of the gears. Therefore, a short program, named `points2stl.cpp`, is written in C++ and then compiled using the GNU Compiler Collection. To compile the program just enter into the terminal:

```
g++ points2stl.cpp -o points2stl
```

And to run it:

```
./points2stl
```

The program requires several files to be present in its directory. A `solids` file must be provided, for example as follows:

```
3  -1  11
gear0  1913  0  0       0
gear1  1913  0  45.123  0
case   1870  0  0       0
```

The first line indicates the number of solids below, then the minimum z value, and the maximum z value for the STL file. Next, a line for each solid indicates the name, the number of points, the translation in the x direction, the translation in the y direction, and the rotation angle, in rad. Note how the `gear1` solid is displaced towards the y direction. This is because the same list of points is being used for both gears.

For each solid, another file with the name of the solid (in the example: `gear0`, `gear1` and `case`) must be present in the same directory. This file must contain the points of the solid as they were extracted in the previous section:

```
-2.6841909571      23.5344354143
-2.7402671858      23.4064052141
1.9790048057       24.8983171305
2.0492641836       24.7775481
...
```

The points that were extracted in the previous section were not sorted consecutively. Thus, the C++ program has to sort them during runtime. To do that, the program starts with the first point and, to get the next one, it searches for the nearest point that hasn't been already selected. The program keeps going by taking one pair of points at a time. Each of these pair of points is placed at the `maxZ` plane and a copy is placed at the `minZ` plane. Finally the rectangle formed by these four vertices is split into two triangles and written to the output STL file. For the last point, an exception is made so that it connects with the first point and the STL surface is closed.

The C++ source code of the `points2stl` program is shown below, but it is also included in the media that comes with this work.

```
1    #include<fstream>
2    #include<cmath>
3
4    using namespace std;
5
6    bool isPastPoint(int point, int pastPoint[], int n)
7    {
8      int i;
9      for (i=0;i<n;i++) if (point == pastPoint[i]) return 1;
10     return 0;
11   }
12
13   int getNextPoint(int curPoint, int pastPoint[], int n, int nPoints,
14                    double point[][2])
15   {
16     int i, nextPoint;
17     double x1, y1, x2, y2, distance2, minDistance2;
18
19     //Special case for the last point to meet the first point:
20     if (n==nPoints) return pastPoint[0];
21
22     x1 = point[curPoint][1];
23     y1 = point[curPoint][2];
24     nextPoint = -1;
25     minDistance2 = 1.e10;
26
27     for (i=0; i<nPoints; i++)
28     {
29       x2 = point[i][1];
30       y2 = point[i][2];
31       distance2 = (x2-x1)*(x2-x1)+(y2-y1)*(y2-y1);
32       if (distance2 < minDistance2 and not isPastPoint(i,pastPoint,n))
33       {
34         minDistance2 = distance2;
35         nextPoint = i;
36       }
37     }
38
39     return nextPoint;
40   }
41
42   int main()
43   {
44     int nSolids, nPoints, i, s;
45     int curPoint, nextPoint;
46     double x, y, r, angle, dx, dy, dAngle, z0, z1;
47     char solidName[20];
48
49     ifstream solidsFile;
50     ofstream outputFile;
51
52     solidsFile.open("./solids");
53     outputFile.open("./triSurface.stl", ios::out | ios::trunc);
54
55     solidsFile>>nSolids>>z0>>z1;
56
```

```
57      for (s=0; s<nSolids; s++)
58      {
59        solidsFile>>solidName>>nPoints>>dx>>dy>>dAngle;
60
61        ifstream pointsFile;
62        pointsFile.open(solidName);
63
64        int pastPoint[nPoints];
65        double point[nPoints][2];
66        for (i=0; i<nPoints; i++) {pointsFile>>point[i][1]>>point[i][2];}
67        pointsFile.close();
68
69        for (i=0; i<nPoints; i++)
70        {
71          x = point[i][1];
72          y = point[i][2];
73          r = sqrt(x*x + y*y);
74          angle = atan2(y,x) + dAngle;
75          point[i][1] = r * cos(angle) + dx;
76          point[i][2] = r * sin(angle) + dy;
77        }
78
79        outputFile<<"solid "<<solidName<<"\n";
80
81        curPoint = 0;
82        nextPoint = 0;
83        i = 0;
84        while (i<nPoints)
85        {
86          curPoint = nextPoint;
87          pastPoint[i] = curPoint;
88          i++;
89          nextPoint = getNextPoint(curPoint, pastPoint, i, nPoints, point);
90
91           x = point[curPoint][1];
92           y = point[curPoint][2];
93          dx = point[nextPoint][1];
94          dy = point[nextPoint][2];
95
96          outputFile<<" facet normal "<<(y-dy)<<" "<<(dx-x)<<" 0.0\n";
97          outputFile<<"  outer loop\n";
98          outputFile<<"   vertex "<< x<<" "<< y<<" "<<z0<<"\n";
99          outputFile<<"   vertex "<<dx<<" "<<dy<<" "<<z0<<"\n";
100         outputFile<<"   vertex "<<dx<<" "<<dy<<" "<<z1<<"\n";
101         outputFile<<"  endloop\n  endfacet\n";
102
103         outputFile<<" facet normal "<<(y-dy)<<" "<<(dx-x)<<" 0.0\n";
104         outputFile<<"  outer loop\n";
105         outputFile<<"   vertex "<< x<<" "<< y<<" "<<z0<<"\n";
106         outputFile<<"   vertex "<< x<<" "<< y<<" "<<z1<<"\n";
107         outputFile<<"   vertex "<<dx<<" "<<dy<<" "<<z1<<"\n";
108         outputFile<<"  endloop\n  endfacet\n";
109       }
110       outputFile<<"endsolid "<<solidName<<"\n";
111     }
112
113     solidsFile.close();
114     outputFile.close();
115     return 0;
116   }
```

The resulting STL file can be loaded directly into ParaView (File, Open). Note how each solid is colored differently. Having different solids is the key in order to apply different boundary conditions to each one.

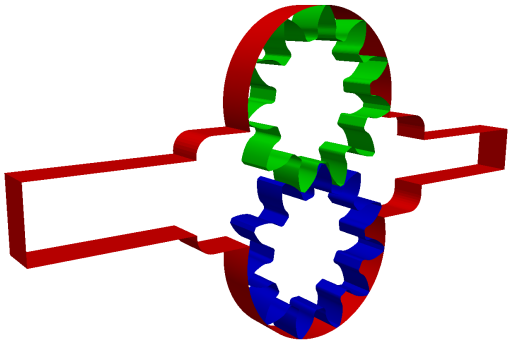


Figure 5.4: STL file displayed in ParaView.

The file system of the case is depicted in Figure 5.5, where both the input and output files are shown, as well as both the C++ source and the executable binary program:

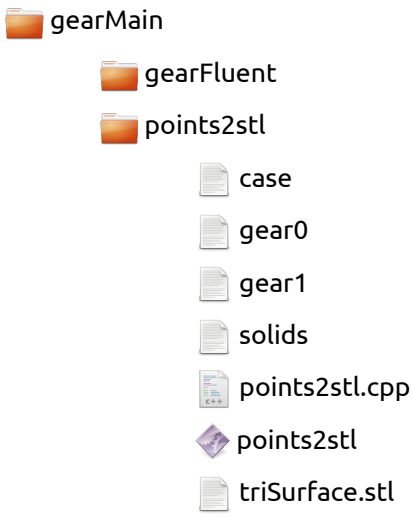


Figure 5.5: File system of the `points2stl` case.

5.4 Meshing

Meshing is probably the trickiest part of the whole study. As has been stated previously, since the geometry is quite complex, `snappyHexMesh` is required. The meshing procedure will be quite similar as that of the `wingMotion` tutorial. The same file system is adopted, as depicted in Figure 5.6, and the required files can be copied from the `wingMotion_snappyHexMesh` directory, and then modified as shown here.

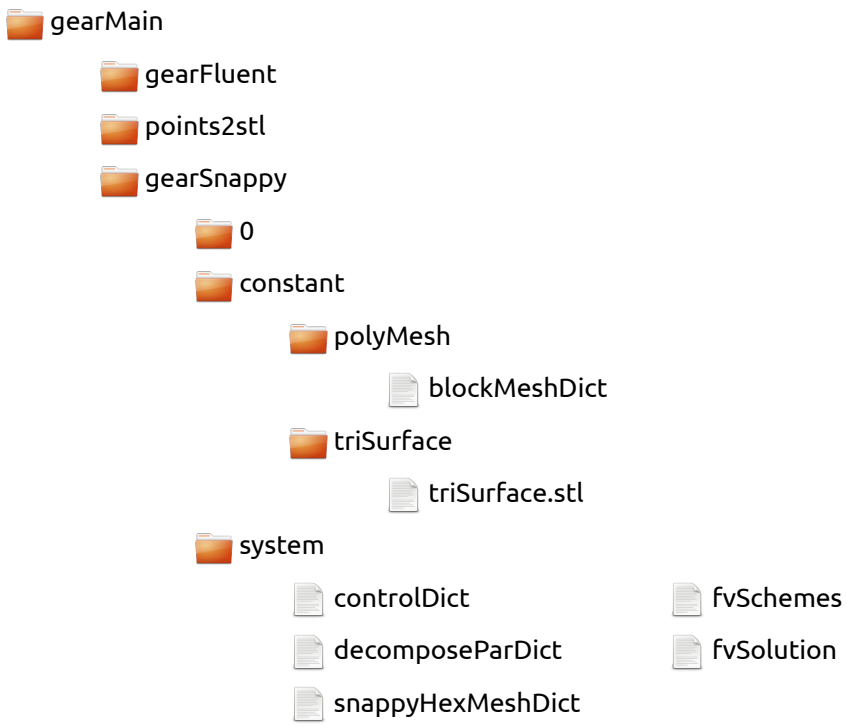


Figure 5.6: File system of the `gearSnappy` case.

5.4.1 blockMesh

Meshing with `snappyHexMesh` requires several actions to be performed. The first one is to create a background mesh using `blockMesh`. The background mesh must be one-cell thick in order to perform a two-dimensional simulation, with `empty` patches at its front and back boundaries. The `blockMeshDict` file must be edited to create a mesh of the approximate size of the STL geometry, which can be checked from ParaView.

The vertices and blocks description are as follows:

```
convertToMeters 1;

vertices
(
      //Front
      (-86 -30 0)  //0
      ( 86 -30 0)  //1
      ( 86  75 0)  //2
      (-86  75 0)  //3

      //Back
      (-86 -30 2)  //4
      ( 86 -30 2)  //5
      ( 86  75 2)  //6
      (-86  75 2)  //7

);
```

```
blocks
(
      hex (0 1 2 3 4 5 6 7) (200 120 1) simpleGrading (1 1 1)
);
```

Note that the dimensions of the block (and the STL file) are in millimeters. To work in meters the whole mesh will have to be scaled at the end of the meshing process. This is not strictly needed; OpenFOAM does not care about units, just dimensions. Thus it is irrelevant if you work using the Imperial System, the Metric System, or any other system (such as using millimeters for longitudes).

However one must take care, because all the input and output variables must share the same units. So, to avoid any trouble this may cause, during the meshing process longitudes will be in millimeters, but after that the Metric System will take over and the mesh will be scaled to comply with it.

Next, no curved edges should appear in the block:

```
edges
(
);
```

The rest of the `blockMeshDict` file defines the different boundaries:

```
boundary
(
    fixedWall
    {
        type wall;
        faces
        (
            (0 1 5 4) //bottom
            (2 3 7 6) //top
        );
    }

    inletPatch
    {
        type patch;
        faces
        (
            (3 0 4 7)
        );
    }

    outletPatch
    {
        type patch;
        faces
        (
            (1 2 6 5)
        );
    }
```

```
        frontEmpty
        {
            type empty;
            faces
            (
                (3 2 1 0)
            );
        }


        backEmpty
        {
            type empty;
            faces
            (
                (4 5 6 7)
            );
        }
    );
```

Finally, no pair of patches needs to be merged.

```
    mergePatchPairs
    (
    );
```

5.4.2 snappyHexMesh

Once the background mesh is created (by using the `blockMesh` command), it is time for `snappyHexMesh` to refine the mesh and adapt it to the geometry that was just created in STL format. The first entries of the `snappyHexMeshDict` file indicate the steps that will be performed when `snappyHexMesh` runs. The layer addition process is not of interest for this work, so let's start with activating the castellated mesh and the snap processes first.

```
    castellatedMesh true;
    snap            true;
    addLayers       false;
```

It will be seen further ahead that it is not a good idea to perform the snapping at this point but let's leave this as it is for now.

The next entry defines the file from which the geometry will be loaded, as well as any refinement boxes the user may wish to define. The `triSurface.stl` file is loaded from the `./constant/triSurface/` directory, and it is the file that was generated with the `points2stl` C++ program.

At this point no refinement boxes will be used, but the entry is left in the file, commented out, so that adding one box can be done quickly should the user want to.

```
geometry
{
    triSurface.stl
    {
        type triSurfaceMesh;
        name gear;
    }

    //refinementBox
    //{
    //    type searchableBox;
    //    min (-30. -30. 0.);
    //    max ( 30.  75. 10.);
    //}
};
```

Next in the file are the controls for the `castellatedMesh`. The first controls set limits to the process in terms of number of cells. The values can be adjusted at user discretion, the ones presented here worked reasonably well:

```
castellatedMeshControls
{
    maxLocalCells        700000;
    maxGlobalCells       1400000;
    minRefinementCells   10;
    maxLoadUnbalance     0.10;
    nCellsBetweenLevels  3;
```

Next, the explicit feature edge refinement is a feature (forgive the repetition) recently added to OpenFOAM, that allows a better discretization on certain edges the domain may have, which previously experienced some distortion. Since the mesh under study is two-dimensional no edge should have this problem, and this feature is commented out:

```
    features
    (
        //{
        //    file "someLine.eMesh";
        //    level 2;
        //}
    );
```

After a score of tests the levels of refinement presented here were selected as the best choice in terms of quality and time. Too much refinement implies a much higher meshing time, which would be prohibitive if one recalls that multiple meshes are going to be made.

On the other hand, too low levels would split the mesh at points where the teeth and the case are so close that the mesh after those points would be marked as unreachable and removed from the rest of the mesh, as seen on Figure 5.7.

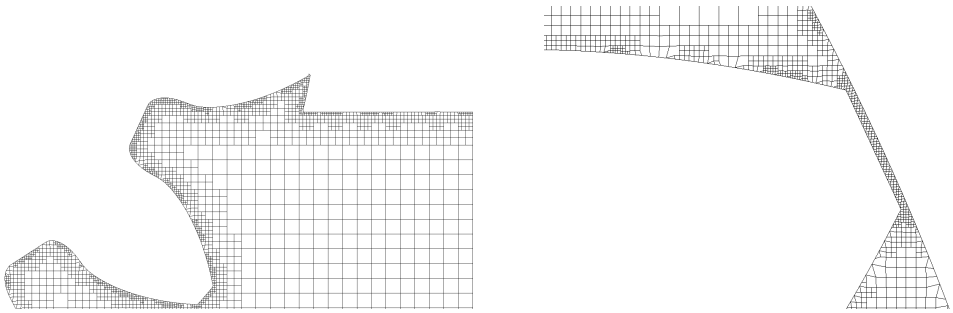


Figure 5.7: Broken mesh due to a low refinement (left) and correct mesh (right).

Again the refinement regions entry is commented out, since no refinement boxes are being used. If refinement boxes are being used, the user must uncomment these too.

```
    refinementSurfaces
    {
        gear
        {
            level (3 5);
        }
    }

    resolveFeatureAngle 30;

    refinementRegions
    {
        //refinementBox
        //{
        //    mode inside;
        //    levels ((1E15 2));
        //}
    }
```

Finally the last `castellatedMesh` controls are listed. The `locationInMesh` is selected so that it is not in a face of any cell, but inside a cell. Any part of the mesh that cannot be reached from this point after refinement is eliminated. As it has been said, if the refinement is not high enough, the part of the mesh behind the teeth will be deleted.

```
    locationInMesh (-85.91 15.01 0.0000000005);
    allowFreeStandingZoneFaces true;
}
```

Next the snapping controls are left more or less at the default values:

```
snapControls
{
    nSmoothPatch 3;
    tolerance 4.0;
    nSolveIter 3;
    nRelaxIter 5;
    //nFeatureSnapIter 10;
}
```

Since the layer addition process was deactivated at the beginning of the file, those controls are of no interest. The mesh quality controls are left at default values too, so the `snappyHexMeshDict` file is ready.

However, several problems arise when trying to perform the `snappyHexMesh` run. First, all programs in OpenFOAM are three-dimensional, and `snappyHexMesh` is not an exception. Because of this, `snappyHexMesh` refines the mesh through the *z* direction, obliterating the one-cell thickness that was selected with `blockMesh`.

This is a huge drawback, because to perform a two-dimensional simulation in OpenFOAM the mesh must have this one-cell thickness and `empty` front and back patches. By adding cells through the *z* direction, `snappyHexMesh` renders the mesh useless. Also, the process of snapping takes much longer than expected, which is a problem if multiple meshes are to be generated at different positions of the gears.

The following steps are needed to solve these problems. First, parallel execution of `snappyHexMesh` is developed in order to cut down meshing times. Next the mesh is made two-dimensional again with help of the `extrudeMesh` tool.

5.4.3 decomposePar

The parallel processing is performed by splitting the domain into multiple sub-cases folders, then the solver (or the meshing program in this case) runs all cases at once, keeping them in communication. In OpenFOAM this can be done automatically by means of the `decomposePar` tool. As with most OpenFOAM applications, the `decomposePar` tool requires its own `decomposeParDict` file.

Given that the computer in which the meshing is being executed has an eight-core Intel i7 processing unit, six of those cores are utilized to perform the parallel meshing. The decomposing method is hierarchical, a simple method that divides the domain in equal parts in the number and order specified for each direction.

```
numberOfSubdomains   6;
method               hierarchical;

hierarchicalCoeffs
{
    n               (3 2 1);
    delta           0.001;
    order           xyz;
}
```

The domain can now be decomposed by running the `decomposePar` command after running the `blockMesh` command. Six folders are created, named `processor0` to `processor5`, inside the `gearSnappy` directory. Inside each of those folders a sixth of the background mesh is set for refinement. It is recommended to run the following command just after decomposing the domain, before the `snappyHexMesh` process:

```
foamJob -s -p renumberMesh -overwrite
```

Then the snapping is run by entering the command:

```
foamJob -s -p snappyHexMesh -overwrite
```

The `foamJob` command allows the execution of OpenFOAM applications with some special options, and parallel processing is one of them. This command stores all command-line output to a log file. The `-s` option forces this output to be displayed in the Terminal too. The `-p` option executes the application in parallel. The `-overwrite` option forces `renumberMesh` and `snappyHexMesh` to overwrite the background mesh with the renumbered or refined mesh, instead of storing it in a new time directory.

The `renumberMesh` tool reorders the numbering of the points in each processor directory in order to make it more efficient.

During the `snappyHexMesh` process the load of each processor is balanced after each step, if needed, in order to even the load of all of them up to a certain margin specified in the `maxLoadUnbalance` entry in the `snappyHexMeshDict` file.

Once the meshing process is over the mesh can be reconstructed by using the following command:

```
reconstructParMesh -mergeTol 1e-6 -constant
```

The `-mergeTol` option can be adjusted as needed, while the `-constant` option indicates to the `reconstructParMesh` tool that the mesh is stored in the `./constant/polyMesh` directory, and works in conjunction with the `-overwrite` option of `snappyHexMesh`. In case the `-overwrite` option was not used, the option `-time N` (where `N` is the time directory in which the mesh was stored), or the option `-latestTime` if the mesh is stored in the last directory, can be used.

After the mesh has been reconstructed the `processor0` to `processor5` folders can be deleted and the mesh is ready for the next step.

5.4.4 extrudeMesh

As it has been said, `snappyHexMesh` refines the mesh in all directions, including the *z* direction. This makes the mesh unusable as a two-dimensional mesh. But there is a tool called `extrudeMesh` that can generate a mesh by extruding a patch of another mesh. It is used in the `wingMotion` tutorial, and as it can be seen, it requires a separate case directory in order to work.

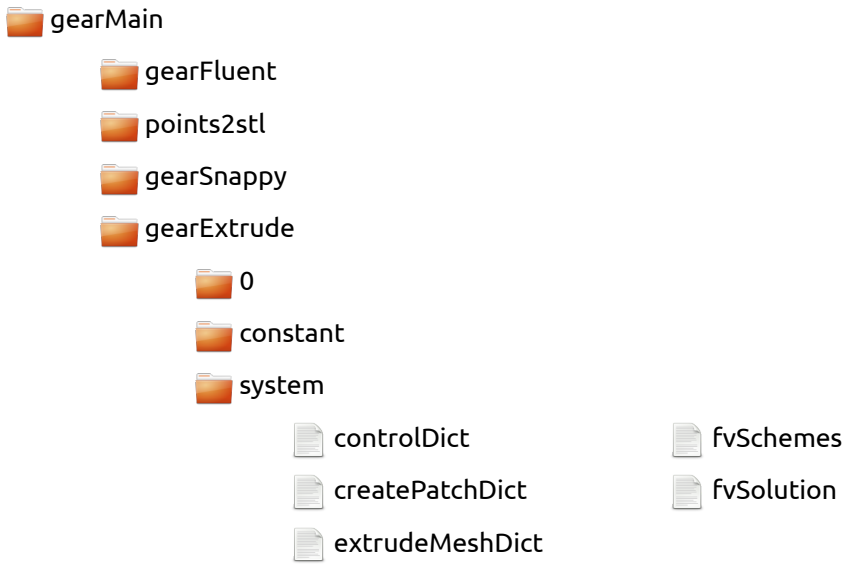


Figure 5.8: File system of the `gearExtrude` case.

The `extrudeMeshDict` file contains all the information needed in order to perform the extrusion.

```
constructFrom       patch;
sourceCase          "../gearSnappy";
sourcePatches       (frontEmpty);
exposedPatchName    backEmpty;
flipNormals         false;
extrudeModel        linearNormal;
nLayers             1;
expansionRatio      1.0;

linearNormalCoeffs
{
    thickness       1.0;
}

mergeFaces          false;
```

The `constructFrom` entry indicates that a patch from a mesh is going to be used as the base for the extrusion. The source case is set to the `gearSnappy` directory, which is located in the same directory as `gearExtrude`. The `frontEmpty` patch is selected as the

source patch, and the patch that is going to be created in front of it is called `backEmpty`. The extrusion is chosen to be linear, as the target is to obtain a two-dimensional mesh. This tool can generate also spherical or cylindrical extrusions. The number of cells the mesh must have is one, as indicated by the `nLayers` entry. The `expansionRatio` and the `thickness` have no special influence on the two-dimensional mesh, and the `mergeFaces` entry is interesting only for 360° cylindrical extrusions.

As a side note, it is interesting to know that the `extrudeMesh` tool can also extrude a two-dimensional surface mesh stored in a surface file such as an STL. In such a case the first lines of the `extrudeMeshDict` file should read like this:

```
constructFrom  surface;
surface        "./constant/triSurface/mesh.stl";
flipNormals    false;
...
```

This is interesting because the user may like to create the two-dimensional mesh using another meshing software, such as Salome, instead of using `snappyHexMesh`, and then the mesh could be exported as an STL file from that software and easily imported into OpenFOAM using `extrudeMesh`.

In this case it should be noted that the definition of the vertices of all triangles in the STL file must follow the right-hand rule to determine the normal to the surface and the direction of the extrusion.

Back to the topic, a `createPatchDict` file is also added, its main interest being renaming the patches created by the `extrudeMesh` tool, and, most important, removing the `fixedWall` patches that were defined on top and bottom of the background `blockMesh`, and that are not used after the `snappyHexMesh` process takes place.

```
pointSync false;

patches
(
    {
        name gear0;

        patchInfo
        {
            type wall;
        }

        constructFrom patches;
        patches (gear_gear0);
    }
```

```
    {
        name gear1;

        patchInfo
        {
            type wall;
        }

        constructFrom patches;
        patches (gear_gear1);
    }

    {
        name case;

        patchInfo
        {
            type wall;
        }

        constructFrom patches;
        patches (gear_case);
    }
);
```

The names of the patches could be different from those created by `snappyHexMesh`, but there is no need to do so anyway. Only the `gear_` part of the name is removed from those patches. So the only important effect of running `createPatch` is removing the unused patches, `fixedWall` in this case, from the mesh.

5.4.5 runMesh

After all the steps to generate a mesh from the STL file created in section 5.3 have been defined, a small bash script called `runMesh` is written in order to automate the execution of all the applications. It is placed inside the `gearMain` directory. Initially it looks like this:

```
#!/bin/bash

. /opt/openfoam210/etc/bashrc

#snappyHexMesh
cd gearSnappy
rm -rf log processor* constant/polyMesh/*
cp constant/blockMeshDictCopy constant/polyMesh/blockMeshDict

blockMesh
decomposePar
foamJob -s -p renumberMesh -overwrite
foamJob -s -p snappyHexMesh -overwrite
reconstructParMesh -mergeTol 1e-6 -constant
```

```
rm -rf processor*

#extrudeMesh
cd ../gearExtrude
rm -rf constant/polyMesh/*
extrudeMesh
createPatch -overwrite

#scale to mm
transformPoints -scale "(0.001 0.001 0.001)"
```

Bash is just a scripting language that can automate the commands that are going to be introduced in the Terminal. Each line in the bash script is a command that is entered into the Terminal as if the user did so manually, and once that command ends the next one is entered.

Several commands have been added to complete the procedure. The first command, `. /opt/openfoam210/etc/bashrc`, is the same that must be included in the user's `~/.bashrc` file during installation of OpenFOAM in order to be able to use OpenFOAM commands. This ensures that when launching the bash script OpenFOAM commands will be available.

Next, the working directory changes to `gearSnappy`, and the files inside the `constant/polyMesh` directory are removed, as well as any `processor*` folder that could have been left at a previous run. After this, a copy of the `blockMeshDict` file that is saved as `constant/blockMeshDictCopy` is moved into the `constant/polyMesh` directory, and then `blockMesh` is run. This is done to ensure that a clean mesh is being used as the background mesh for `snappyHexMesh`.

After running `blockMesh` the mesh is decomposed, renumbered in parallel, and then `snappyHexMesh` runs in parallel too. After the mesh is reconstructed the `processor` folders are removed again.

Finally, the working directory is changed to `extrudeMesh`, where again the `constant/polyMesh` directory is cleaned, and the `extrudeMesh` and `createPatch` commands are run. As it was said in section 5.4.1 the mesh is scaled at the end of the complete meshing process, as to be dimensioned according to the Metric System.

Once the `runMesh` script finishes running, a two-dimensional mesh is obtained inside the `gearExtrude/constant/polyMesh` directory.

5.4.6 Improving the Meshing Procedure

But the first obtained results are far from being optimal. As can be seen on Figure 5.9 and Figure 5.10 the borders of the mesh are badly distorted, like a serrated knife's edge. Obviously such a mesh is completely unusable. Figures show the `frontEmpty` patch.

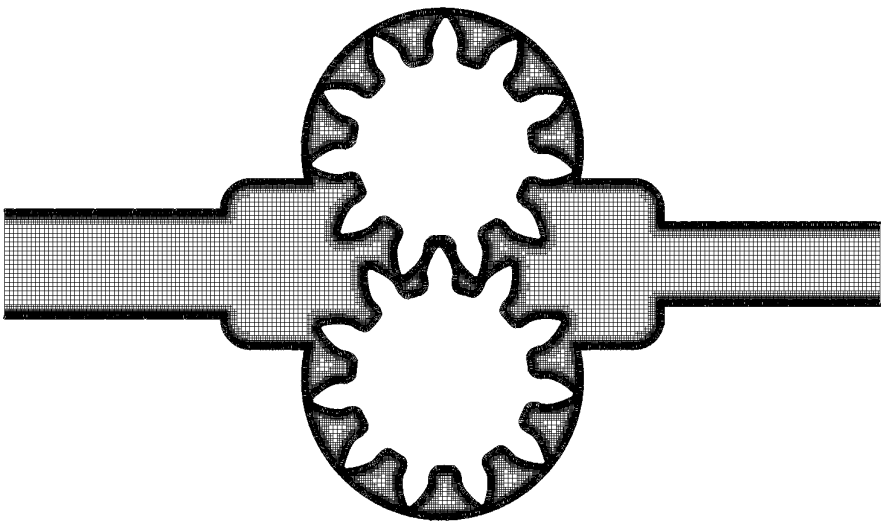


Figure 5.9: The mesh boundary is badly messed after the extrusion.

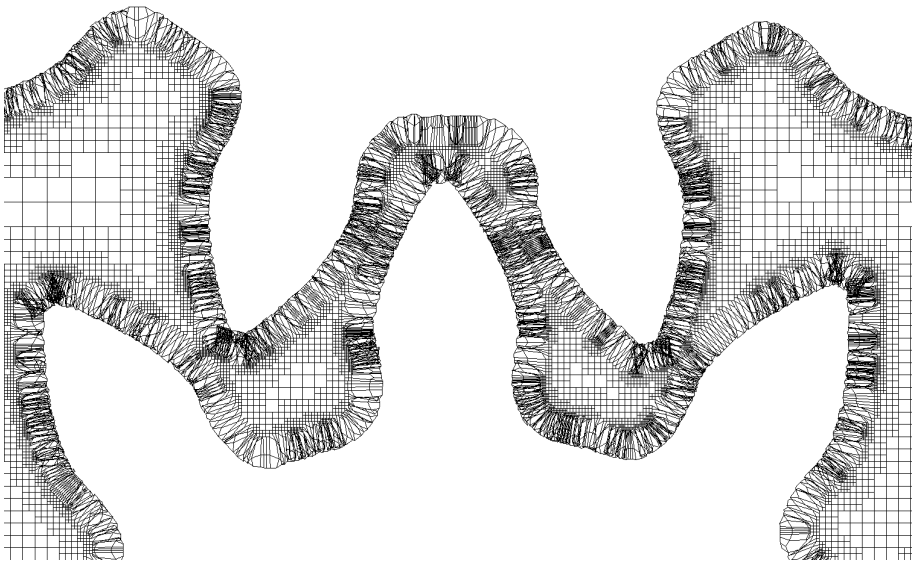


Figure 5.10: Detail of the mesh.

And the `checkMesh` output doesn't make things look any better:

```
[...]

Checking topology...
    Boundary definition OK.
    Cell to face addressing OK.
    Point usage OK.
    Upper triangular ordering OK.
    Face vertices OK.
   *Number of regions: 5
    The mesh has multiple regions which are not connected by any face.
  <<Writing region information to "0/cellToRegion"

[...]

Checking geometry...
    Overall domain bounding box (-0.0863136 -0.0277598 -0.001) (0.0861261
0.0729118 0.000417316)
    Mesh (non-empty, non-wedge) directions (0 0 0)
    Mesh (non-empty) directions (0 0 0)
 ***Number of edges not aligned with or perpendicular to non-empty
directions: 316150
  <<Writing 169410 points on non-aligned edges to set nonAlignedEdges
    Boundary openness (-4.57826e-18 4.36446e-17 3.31683e-14) OK.
    Max cell openness = 1.27921e-15 OK.
    Max aspect ratio = 0 OK.
    Minumum face area = 2.94395e-11. Maximum face area = 8.75e-07.  Face area
magnitudes OK.
    Min volume = 1.33031e-13. Max volume = 7.525e-10.  Total volume =
4.74499e-06.  Cell volumes OK.
    Mesh non-orthogonality Max: 178.291 average: 37.6479
   *Number of severely non-orthogonal faces: 24111.
 ***Number of non-orthogonality errors: 2581.
  <<Writing 26692 non-orthogonal faces to set nonOrthoFaces
 ***Error in face pyramids: 18804 faces are incorrectly oriented.
  <<Writing 17013 faces with incorrect orientation to set wrongOrientedFaces
 ***Max skewness = 6312.24, 1787 highly skew faces detected which may impair
the quality of the results
  <<Writing 1787 skew faces to set skewFaces
    Coupled point location match (average 0) OK.

Failed 4 mesh checks.

End
```

Several thoughts arise from these results. First, the `extrudeMesh` is probably encountering that the `frontEmpty` patch is not flat, that is, the points do not share the same z coordinate. Fortunately, there is a command, called `flattenMesh`, that does exactly as its name indicates. By running this command, all the points in each `empty` patch of a mesh are moved to the same z coordinate, in order to make the patch flat. Figure 5.11 and Figure 5.12 show how, by adding the `flattenMesh` command to the `runMesh` script, just after the mesh reconstruction takes place, the result is greatly improved, at least visually.

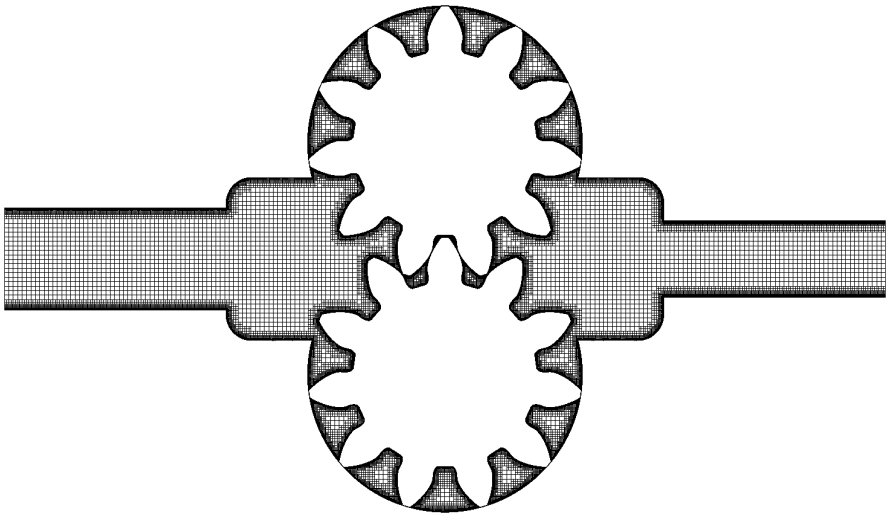


Figure 5.11: The mesh improves greatly when using `flattenMesh`.

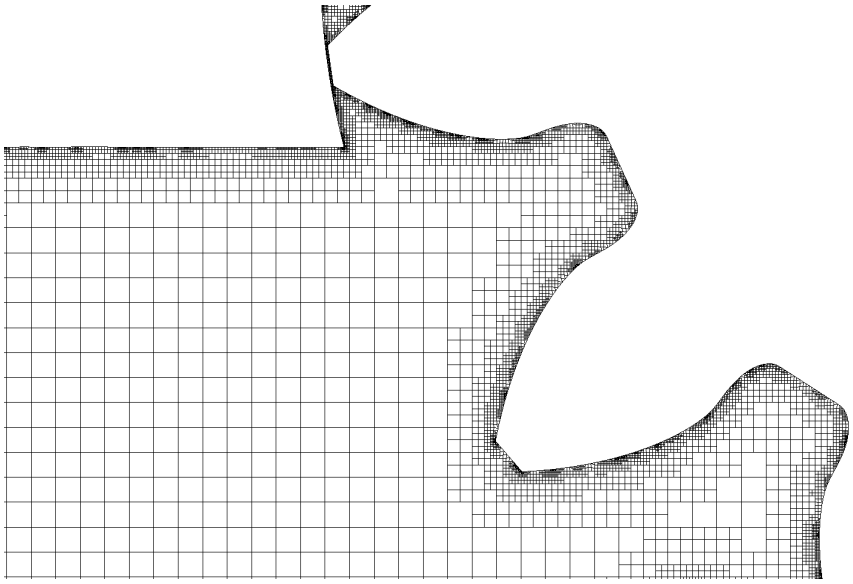


Figure 5.12: Detail of the mesh.

However, by running the `checkMesh` command again one finds that the mesh continues to have great problems:

```
[...]
Checking topology...
    Boundary definition OK.
    Cell to face addressing OK.
    Point usage OK.
    Upper triangular ordering OK.
    Face vertices OK.
   *Number of regions: 5
    The mesh has multiple regions which are not connected by any face.
  <<Writing region information to "0/cellToRegion"
```

```
 [...]
Checking geometry...
    Overall domain bounding box (-0.086 -0.0268349 -0.001) (0.086 0.0719577
0.001)
    Mesh (non-empty, non-wedge) directions (0 0 0)
    Mesh (non-empty) directions (0 0 0)
 ***Number of edges not aligned with or perpendicular to non-empty
directions: 256716
  <<Writing 167262 points on non-aligned edges to set nonAlignedEdges
    Boundary openness (-1.31351e-17 4.59727e-17 -9.04726e-15) OK.
 ***Open cells found, max cell openness: 0.000920221, number of open cells 5
  <<Writing 5 non closed cells to set nonClosedCells
 ***Zero or negative face area detected.  Minimum area: 0
  <<Writing 5 zero area faces to set zeroAreaFaces
    Min volume = 1.66667e-300. Max volume = 0.7525.  Total volume = 4084.85.
Cell volumes OK.
    Mesh non-orthogonality Max: 89.031 average: 9.34645
   *Number of severely non-orthogonal faces: 8.
    Non-orthogonality check OK.
  <<Writing 8 non-orthogonal faces to set nonOrthoFaces
 ***Error in face pyramids: 11 faces are incorrectly oriented.
  <<Writing 11 faces with incorrect orientation to set wrongOrientedFaces
 ***Max skewness = 38.6145, 21 highly skew faces detected which may impair
the quality of the results
  <<Writing 21 skew faces to set skewFaces
    Coupled point location match (average 0) OK.

Failed 5 mesh checks.

End
```

Also, a few faces are found out of place after a closer visual inspection of the mesh:

Figure 5.13: Errors on some faces that are out of place.

These errors require thinking about how `snappyHexMesh` works, in order to find what causes them. As it was said in section 5.4.2, the `snappyHexMesh` process consists of three main steps, to be remembered: `castellatedMesh`, `snap`, and `addLayers`.

The last process, `addLayers`, is not being used in this work. The first one, `castellatedMesh`, consists of multiple refinement iterations. In rough words, starting with the background mesh created with `blockMesh`, `snappyHexMesh` checks which cells are in contact with the STL surface of reference. Those cells are refined, that is, since all cells are hexahedra, refined cells are split in eight smaller hexahedra. Logically this process of splitting cells is not able to change the orientation of edges or faces, so the `castellatedMesh` step can't be the cause of the problems the mesh is having.

Then the only left cause for these problems is the `snap` process. Supposedly, during this step the points and faces are moved and aligned with the STL surface. But since, as it has been said, OpenFOAM in general and `snappyHexMesh` in particular work with three-dimensional domains, while the mesh that one wants to obtain in this case is two-dimensional. And since after the `castellatedMesh` step the mesh has multiple cells in the z direction, the `snap` process modifies the orientation of faces and cells in this direction, and badly deteriorates the mesh for the later two-dimensional extrusion.

It is because of this that a new strategy is developed. Until now the `wingMotion` tutorial has been closely followed, using first the `castellateMesh` and `snap` processes, and then extruding the two-dimensional, desired mesh. But now this order will be modified.

First, only the `castellateMesh` step of `snappyHexMesh` will be run, avoiding potential misalignment problems. Next, the mesh will be flattened just in case; since no snap is performed up to this point the `flattenMesh` step may be useless, but it is better to prevent than to heal. After this the mesh can be extruded and finally `snappyHexMesh` is run again, this time with `snap` only.

The file system is arranged as shown in Figure 5.14. This strategy implies having an additional `snappyHexMeshDict` file, as well as a copy of the `triSurface.stl` file, inside the `gearExtrude` directory. The `decomposeParDict` file is needed by `snappyHexMesh`, although for the second time `snappyHexMesh` runs, after `extrudeMesh`, the domain will not be decomposed, as after the mesh is made two-dimensional the `snap` process should run quick enough.

The `gearSnappy/system/snappyHexMeshDict` file reads at the top lines:

```
castellatedMesh true;
snap            false;
addLayers       false;
```

While the one at `gearExtrude/system/snappyHexMeshDict` reads:

```
castellatedMesh false;
snap            true;
addLayers       false;
```

This way the `snap` won't take place until the mesh has been extruded.

Figure 5.14: File system of the `gearSnappy` and `gearExtrude` cases.

Apart from these changes, the patches must now keep the same name between the two `snappyHexMesh` runs. Therefore, the `createPatch` run is moved to after the second `snappyHexMesh` run, in order to rename the gear patches and, most important, remove the unused `fixedWall` patch.

The backup copy of the `blockMeshDict` file, `blockMeshDictCopy` is shown in Figure 5.14 too.

The `runMesh` script is adapted to the new meshing strategy. The code is finally:

```
#!/bin/bash

. /opt/openfoam210/etc/bashrc

# clean folders
cd gearSnappy
rm -rf log processor* constant/polyMesh/*
cp constant/blockMeshDictCopy constant/polyMesh/blockMeshDict

# blockMesh background mesh
blockMesh

# snappyHexMesh 3D castellateMesh
decomposePar
foamJob -s -p renumberMesh -overwrite
foamJob -s -p snappyHexMesh -overwrite
reconstructParMesh -mergeTol 1e-6 -constant
flattenMesh
rm -rf log processor*

# extrudeMesh 2D extrude
cd ../gearExtrude
rm -rf constant/polyMesh/*
extrudeMesh

# snappyHexMesh 2D snap
snappyHexMesh -overwrite
createPatch -overwrite

# scale to mm
transformPoints -scale "(0.001 0.001 0.001)"
```

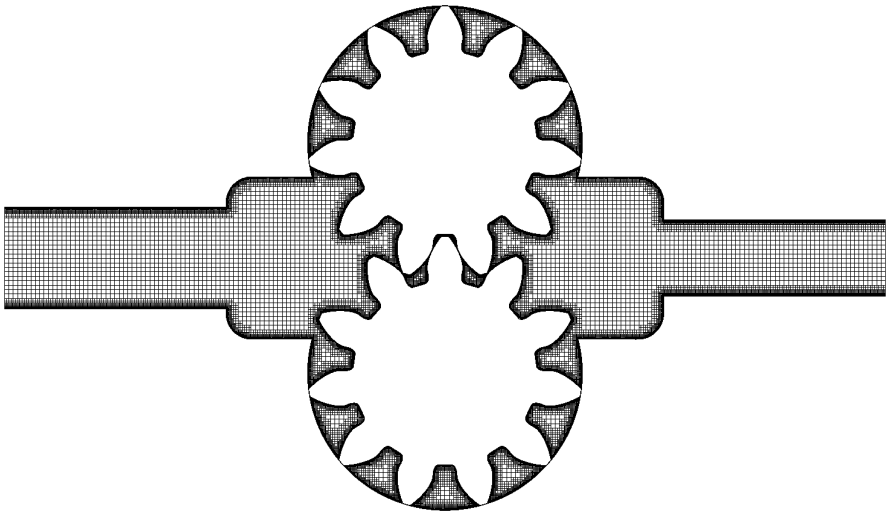


Figure 5.15: Mesh correctly generated with the final `runMesh` script.

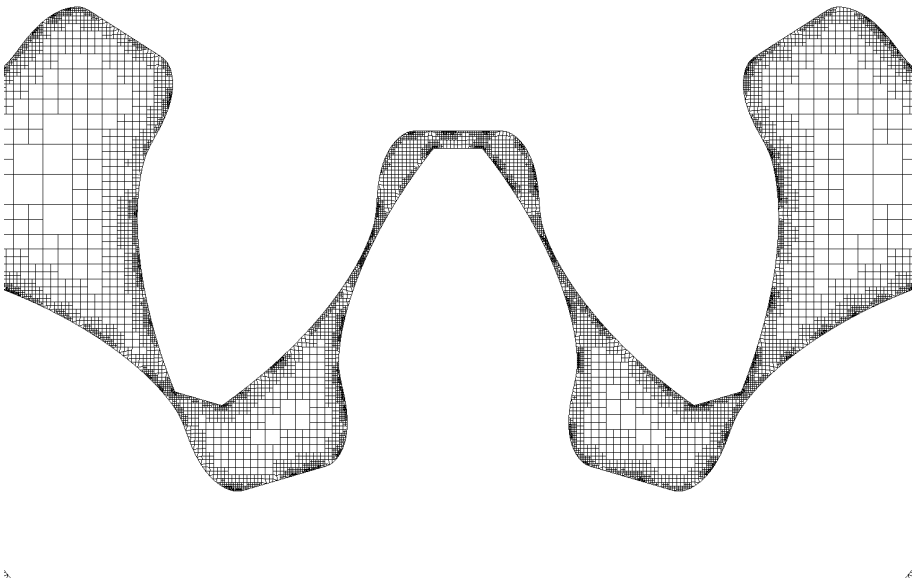


Figure 5.16: Mesh correctly generated. Detail of the gear meshing zone.

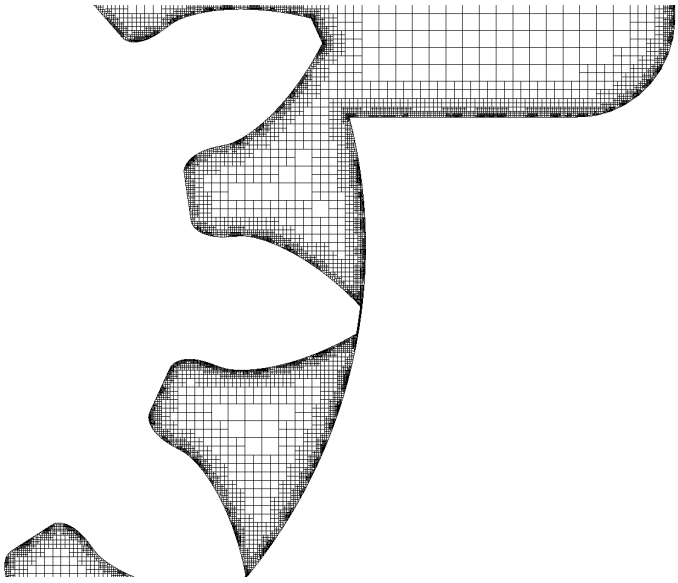


Figure 5.17: Mesh correctly generated. Detail of the casing zone.

Visual inspection yields positive results, with no out-of-place faces showing. Also, after running the script the `checkMesh` utility is run again, with much better results:

```
[...]

***Max skewness = 4.05358, 1 highly skew faces detected which may impair the
quality of the results
  <<Writing 1 skew faces to set skewFaces

Failed 1 mesh checks.
```

This single skewed face should not represent a problem for the simulation.

5.5 Moving the Mesh

Once a mesh has been generated it is time to start moving it. The target is to check how much the gears can rotate, and how much deformation the mesh can withstand, before the deformation becomes too much and a new mesh is needed to take over.

First of all a new case directory is created. Secondly the boundary conditions for pressure and velocity, as well as the movement of the mesh, are introduced into the case. Next a new boundary condition for the rotating motion of the gears is developed. After that the different parameters of the case are determined. And finally a bash script is written to run the moving of the mesh.

5.5.1 Creating a New Case Directory

The kind of movement required is somehow similar to the one in the `movingCone` tutorial, where an horizontal displacement of a surface is imposed.

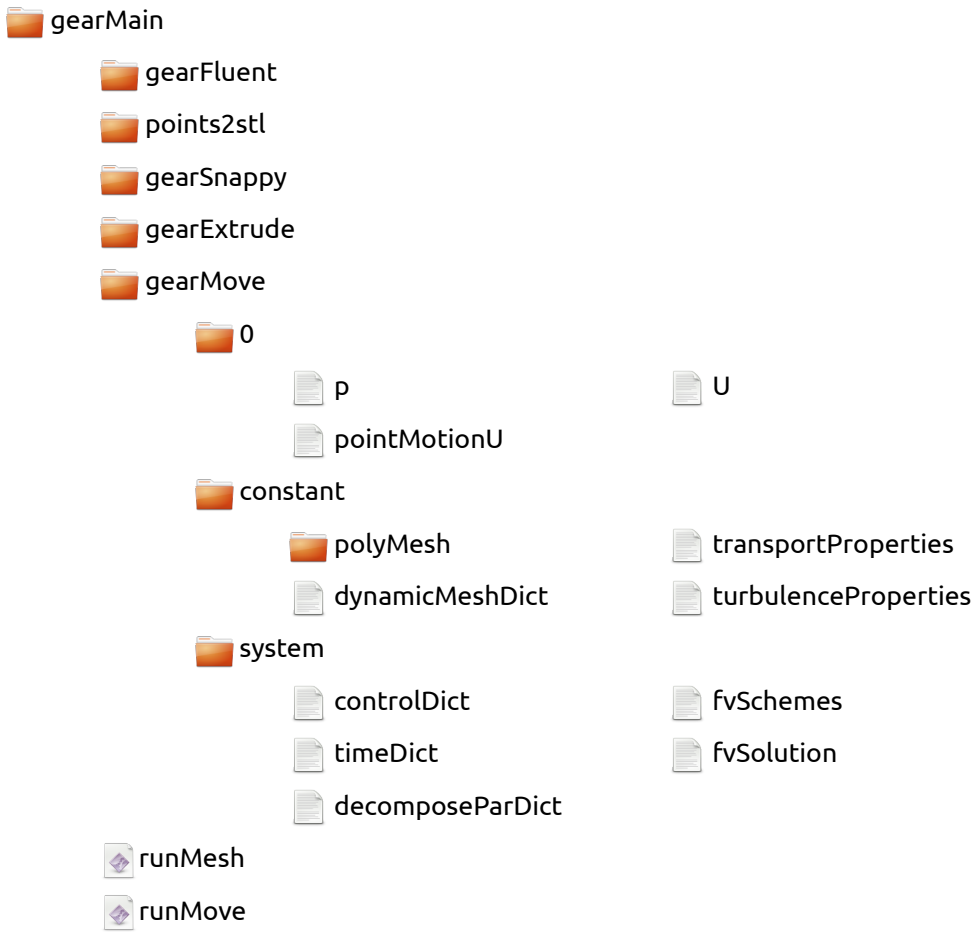


Figure 5.18: File system of the `gearMove` case.

In the case of the gears the displacement is also imposed, but it being a rotation and not a translation will enforce changes in most files concerning the dynamic mesh. Nevertheless the `movingCone` tutorial is similar enough, and the file system of the `gearMove` case is based on it, as shown in Figure 5.18.

5.5.2 Setting Up the Boundary Conditions

The boundary conditions of an OpenFOAM case are defined inside the first time directory, `0` in this case. Inside the `0` directory there is a file for each field considered, where boundary conditions are defined in a per-patch basis, that is, each patch may have a different boundary condition. The same is true in reverse order: for two surfaces to have different boundary conditions they must be defined as separate patches.

Boundary conditions for the pressure `p` and the velocity `U` are chosen among the ones available in OpenFOAM. First, the pressure file `p` is shown here by sections. The header reads:

```
FoamFile
{
    version     2.0;
    format      ascii;
    class       volScalarField;
    object      p;
}
```

In the `class` entry it is indicated that the pressure is a volumetric scalar field. This will have some importance regarding the boundary file for the motion of the gears.

```
dimensions      [0 2 -2 0 0 0 0];

internalField   uniform 0;
```

Dimensions are specified as powers of the fundamental dimensions. As it was mentioned previously, OpenFOAM does not use any units inherently. Operations must be performed using consistent units of measurement; in particular, addition, subtraction and equality are only physically meaningful for properties of the same dimensional units. As a safeguard against implementing a meaningless operation, OpenFOAM attaches dimensions to field data and physical properties and performs dimension checking on any tensor operation [3]. As long as dimensions agree the user can choose any set of units. Table 5.1 shows the order in which dimensions are defined, as well as typical working units.

Number	Dimension	SI units		USCS units	
1	Mass	kilogram	kg	pound-mass	lbm
2	Length	meter	m	foot	ft
3	Time	second	s	second	s
4	Temperature	Kelvin	K	degree Rankine	°R
5	Quantity	kilogram-mole	kgmol	pound-mole	lbmol
6	Current	Ampere	A	Ampere	A
7	Luminous intensity	Candela	cd	Candela	cd

Table 5.1: Base units for SI and USCS, adapted from [3].

It must be noted then that the pressure is specified as having dimensions of length squared over time squared. This is because the pressure with which OpenFOAM works in incompressible solvers is divided by the density of the fluid, in order to make the solution independent of the value of the density. To recover the pressure field in pressure dimensions one must multiply the obtained pressure by the density. As a side note, Table 5.1 is a small glance at the different problems that OpenFOAM can handle.

The value for the initial pressure inside the domain is specified in the `internalField` entry as `0`. Pressures are measured in a relative way; negative pressures may appear, they are only referenced to this pressure origin.

Next the different boundaries are defined. Each patch gets a specific boundary type and other entries that may be required for that boundary type to work, such as `value`.

```
boundaryField
{
    gear0
    {
        type            zeroGradient;
    }

    gear1
    {
        type            zeroGradient;
    }

    case
    {
        type            zeroGradient;
    }

    inletPatch
    {
        type            fixedValue;
        value           uniform 0;
    }
```

```
    outletPatch
    {
        type            zeroGradient;
    }

    frontEmpty
    {
        type            empty;
    }

    backEmpty
    {
        type            empty;
    }
}
```

It can be seen how pressure is fixed to a specific reference value at the inlet, and set to having no gradient in the direction normal to the boundary for the rest of the patches. The `frontEmpty` and `backEmpty` patches are special in the way that they are defined as `empty` for the simulation to be two-dimensional.

Similarly, for the velocity boundary conditions the header of the `U` file reads:

```
FoamFile
{
    version     2.0;
    format      ascii;
    class       volVectorField;
    object      U;
}
```

Here the velocity field is defined as being a vector field, naturally. Dimensions are specified as expected.

```
dimensions      [0 1 -1 0 0 0 0];

internalField   uniform (0 0 0);
```

For the gears a suitable boundary condition has to be found. To do so one option is to modify the `U` file from the `movingCone` tutorial by using an invented boundary condition, such as `invented`, and then trying to run it. Knowing how OpenFOAM handles these kind of errors proves useful in these situations: if a keyword is incorrectly used OpenFOAM displays all the possible values.

In this case, by trying to run the modified tutorial one gets the following list of valid boundary conditions:

```
--> FOAM FATAL IO ERROR:
Unknown patchField type invented for patch type wall
```

```
Valid patchField types are :

64
(
SRFFreestreamVelocity
SRFVelocity
activeBaffleVelocity
[...]
mixed
movingWallVelocity
nonuniformTransformCyclic
[...]
wedge
zeroGradient
)
```

The `movingWallVelocity` boundary condition will work great, as it defines a fixed velocity relative to the moving gear. Finally the boundary conditions are:

```
boundaryField
{
    gear0
    {
        type            movingWallVelocity;
        value           uniform (0 0 0);
    }

    gear1
    {
        type            movingWallVelocity;
        value           uniform (0 0 0);
    }

    case
    {
        type            fixedValue;
        value           uniform (0 0 0);
    }

   inletPatch
    {
        type            zeroGradient;
    }

    outletPatch
    {
        type            zeroGradient;
    }

    frontEmpty
    {
        type            empty;
    }

    backEmpty
    {
        type            empty;
    }
}
```

For the motion of the points more things must be changed from the `movingCone` tutorial, as explained by José Plácido Parra Viol in [2]. As it has been said, in that tutorial the points of the cone surface are set to move horizontally. It is because of this that in the `0` directory of that tutorial a file named `pointMotionUx` appears. This is directly related to the `dynamicMeshDict` file inside the `constant` directory. For the `movingCone` tutorial that file reads:

```
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "constant";
    object      dynamicMeshDict;
}

dynamicFvMesh   dynamicMotionSolverFvMesh;
motionSolverLibs ( "libfvMotionSolvers.so" );
solver          velocityComponentLaplacian x;
diffusivity     directional ( 1 200 0 );
```

It can be seen that the `solver` entry is set to `velocityComponentLaplacian x`. For the gears to rotate the motion of the points will have multiple components, so this solver is not interesting. To find an interesting solver one can follow the same trial-and-error strategy as before. By defining the solver as `invented` and trying to run the tutorial one gets the following error:

```
--> FOAM FATAL ERROR:
Unknown solver type invented

Valid solver types are:

7
(
displacementComponentLaplacian
displacementInterpolation
displacementLaplacian
displacementLayeredMotion
displacementSBRStress
velocityComponentLaplacian
velocityLaplacian
)
```

It would be interesting to use the `velocityLaplacian` solver, similar to the one used in the `movingCone` tutorial, but for all components of the velocity, not just one. In addition to that, the diffusivity is modified so that both x and y directions have the same value. Different diffusivity models can be applied, but before analyzing them the case

must be up and running. A basic analysis of the different diffusivity models for a cavity with a rotating obstacle is done in [2]. The following entries in the `dynamicMeshDict` file of the `gearMove` case are modified:

```
solver          velocityLaplacian;
diffusivity     directional ( 1 1 0 );
```

Evidently, this `velocityLaplacian` solver requires a different boundary setup to that of the `velocityComponentLaplacian` solver. By trying to run the `movingCone` tutorial with the modified `dynamicMeshDict` file one gets an error explaining that the solver expected to find a file called `pointMotionU`. It is because of this that the `pointMotionUx` file inside the `0` directory is renamed as `pointMotionU` and modified to be a vector field instead of the original scalar field. Thus, the header of the `pointMotionU` file reads:

```
FoamFile
{
    version     2.0;
    format      ascii;
    class       pointVectorField;
    object      pointMotionU;
}
```

Note how the `class` entry is modified from `pointScalarField` to `pointVectorField`. The dimensions are kept, and the value for the internal field now is a uniform vector:

```
dimensions      [0 1 -1 0 0 0 0];

internalField   uniform (0 0 0);
```

Again, to get the right boundary conditions for the gears the trial-and-error procedure is followed. This time however, one finds that there is no boundary condition to enforce a fixed angular velocity:

```
--> FOAM FATAL IO ERROR:
Unknown patchField type invented for patch type wall

Valid patchField types are :

25
(
angularOscillatingDisplacement
angularOscillatingVelocity
calculated
cyclic
cyclicAMI
cyclicSlip
empty
fixedNormalSlip
fixedValue
mixed
```

```
nonuniformTransformCyclic
oscillatingDisplacement
oscillatingVelocity
processor
processorCyclic
slip
surfaceDisplacement
surfaceSlipDisplacement
symmetryPlane
timeVaryingUniformFixedValue
uniformFixedValue
value
waveDisplacement
wedge
zeroGradient
)
```

The `slip` boundary type is of interest for the casing of the gears, as it would allow the points on it to rotate along the boundary in conjunction with the gears, thus little deforming the mesh where the gears and the casing are near. But as it has been said no option seems useful for the gears themselves. It is because of this that a new boundary condition must be implemented.

5.5.3 Creating a User-Defined Boundary Condition

The development of a new boundary condition for OpenFOAM follows closely the procedure presented by José Plácido Parra Viol in [2]. Although OpenFOAM contains multiple different boundary conditions, for the user to select one of them, it may happen, however, that the needed boundary condition is not included in OpenFOAM, as it is the case with the boundary conditions for the rotating gears.

When this happens the user has the option of copying the source code of an existing condition similar to the one needed and modify it, in a way like to the way in which new case directories are created. From the list of available boundary types one can see that the `angularOscillatingVelocity` would be an adequate starting point. The source code for this boundary type can be found in the `/opt/openfoam210/src/fvMotionSolver/pointPatchFields/derived/angularOscillatingVelocity` directory. This directory is copied and renamed as shown in Figure 5.19. The `Make` directory and the `files` and `options` files can be manually created, they are explained further ahead.

First of all, inside both the C and H files, any mention of the word `Oscillating` is removed, just as with the names of both files.

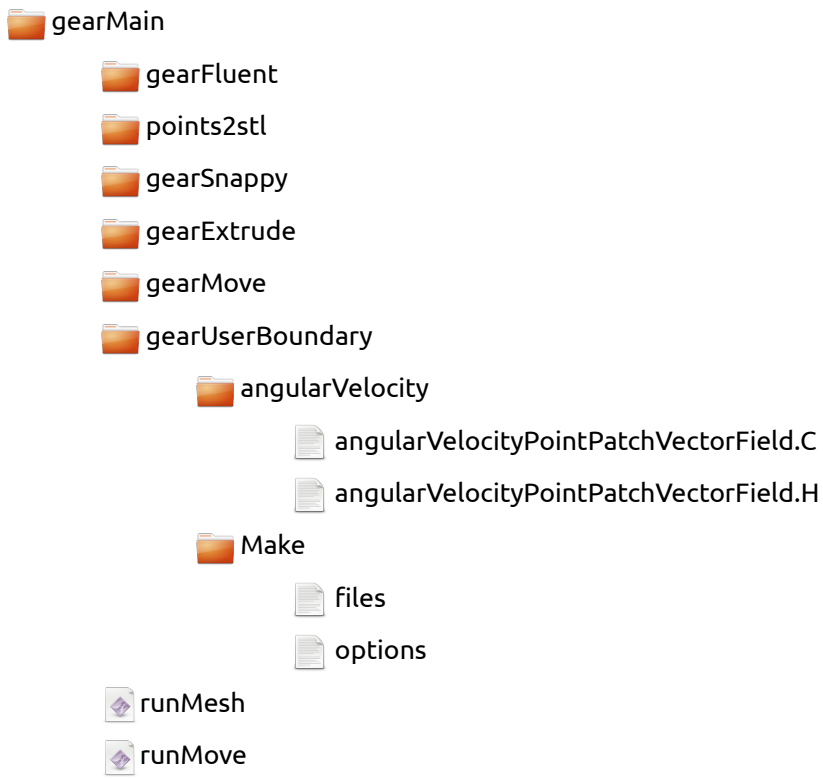


Figure 5.19: Files required to create a user-defined boundary condition.

Next inside the C file, the following equation can be found:

```
scalar angle = angle0_ + amplitude_*sin(omega_*t.value());
```

This code gives the unfamiliarized reader a glimpse of how OpenFOAM is coded. Equations can be written very much like they would be written using math notation. This equation is the one that needs to be modified to obtain the desired fixed angular velocity boundary condition. The new equation reads:

```
scalar angle = angle0_ + omega_*t.value();
```

The `amplitude` variable has been eliminated along with the `sin` function. Each other line of the code in which the `amplitude` variable appears must be eliminated too, from both the C and the H files.

Once this has been done the compilation parameters must be determined. The `files` file inside the `Make` directory should display:

```
angularVelocity/angularVelocityPointPatchVectorField.C
LIB = $(FOAM_USER_LIBBIN)/libAngularVelocityPointPatchVectorField
```

The first line points to the location of the C file with the source code, and the second one to the directory where user libraries for OpenFOAM are stored, followed by the

name of the library that will be created. The directory is stored in the `$FOAM_USER_LIBBIN` variable, and can be easily retrieved by typing at the terminal:

```
echo $FOAM_USER_LIBBIN
```

The `options` file is in charge of pointing to the directory in which the included H files from OpenFOAM are located, and to load the required libraries.

```
EXE_INC = \
-I$(LIB_SRC)/finiteVolume/lnInclude
LIB_LIBS = \
-lfiniteVolume
```

Once all the files are correctly setup the user-defined boundary condition can be compiled by changing to the folder in which the files where stored, `gearUserBoundary` in this case, and running:

```
wmake libso
```

If the output displays at the end a message like:

```
'/home/userName/OpenFOAM/userName-2.1.0/platforms/linux64GccDPOpt/
lib/libAngularVelocityPointPatchVectorField.so' is up to date.
```

Then the user-defined boundary condition library has been correctly compiled. In order to be able to use it, the following line will be added to the `controlDict` file:

```
libs ("libAngularVelocityPointPatchVectorField.so" "libOpenFOAM.so")
```

Once the library is available the trial-and-error message will list it as a valid option when trying to run the code with the `invented` boundary condition again.

```
--> FOAM FATAL IO ERROR:
Unknown patchField type invented for patch type wall

Valid patchField types are :

26
(
angularOscillatingDisplacement
angularOscillatingVelocity
angularVelocity
calculated
cyclic

[...]

zeroGradient
)
```

Now the `pointMotionU` file can have the `boundaryField` dictionary completed:

```
boundaryField
{
    gear0
    {
        type            angularVelocity;
        axis            (0 0 1);
        origin          (0 0 0);
        angle0          0.0;
        omega           52.36; //500 rpm
        value           uniform (0 0 0);
    }

    gear1
    {
        type            angularVelocity;
        axis            (0 0 -1);
        origin          (0 0.045123 0);
        angle0          0.0;
        omega           52.36;
        value           uniform (0 0 0);
    }

    case
    {
        type            slip;
    }

    inletPatch
    {
        type            fixedValue;
        value           uniform (0 0 0);
    }

    outletPatch
    {
        type            fixedValue;
        value           uniform (0 0 0);
    }

    frontEmpty
    {
        type            empty;
    }

    backEmpty
    {
        type            empty;
    }
}
```

As it was mentioned, `slip` is the chosen boundary condition for the casing. Both gears are set with a 500 rpm angular velocity, with the axis of one pointing towards the z direction, while the other axis points towards the $-z$ direction, so that the gear below rotates in counter-clock-wise sense, and the gear on top rotates in clock-wise sense.

If one tries to run the `movingCone` tutorial with these modifications the following error appears:

```
--> FOAM FATAL IO ERROR:
keyword cellMotionU is undefined in dictionary
"/home/userName/Desktop/movingCone/system/fvSolution::solvers"
```

In the `system/fvSolution` file the user defines which solver will be used for each variable to be solved. The original `movingCone` tutorial has an entry for the `cellMotionUx` variable that has to be changed to `cellMotionU`, the keyword that the program expected.

Once this last change is done the boundary condition is ready for use. This new `angularVelocity` boundary condition was first tested using a similar test case as the one presented by José Plácido Parra Viol in [2]. It consists on modifying the `cavity` tutorial by adding a rotating obstacle at its center. Only a few time steps were simulated, in order to check that the boundary condition is working properly, as shown in Figure 5.20. The cavity shown presents two open ends at right and left, and walls at its top and bottom.

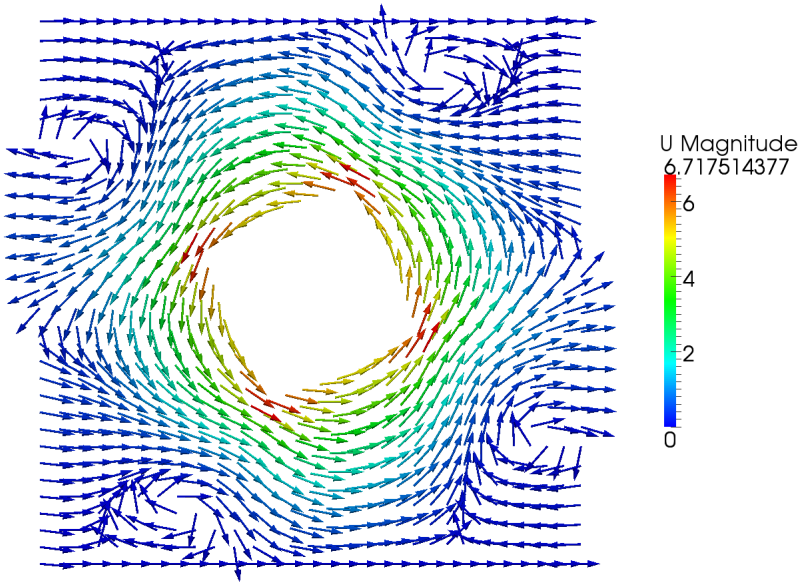


Figure 5.20: Modified `cavity` case for testing the user-defined boundary condition.

5.5.4 Defining the Parameters of the Simulation

After all the contents of the `0` folder are set, with the appropriate boundary conditions, it is time to detail the contents of the other case files inside the `constant` and the `system` directories of Figure 5.18.

Inside the `constant` directory there is a `polyMesh` directory that will contain the mesh generated with the `runMesh` script. The contents of the `dynamicMeshDict` file have already been discussed while developing the user-defined boundary condition in the previous section. The `transportProperties` file reads:

```
transportModel  Newtonian;

nu              nu [ 0 2 -1 0 0 0 0 ] 3.164e-05;
```

Where the `nu` field shows the kinematic viscosity obtained from [1].

As it was mentioned, for this study the simulation is set to laminar. Because of this the `turbulenceProperties` file has only the following entry:

```
simulationType  laminar;
```

Obviously this can be modified if turbulence is going to be simulated. Once the parameters in the `constant` directory have been determined it is time to set the dictionaries in the `system` directory. The `controlDict` file is modified to include an external file called `timeDict`, in order to make some time controls easier to modify later:

```
#include        "timeDict"

libs            ("libAngularVelocityPointPatchVectorField.so"
                 "libOpenFOAM.so")

application     pimpleDyMFoam;

startFrom       startTime;
startTime       $start;

stopAt          endTime;
endTime         $end;

deltaT          $delta;

writeControl    timeStep;
writeInterval   $write;

purgeWrite      0;

writeFormat     binary;
writePrecision  6;
writeCompression off;

timeFormat      general;
timePrecision   6;

runTimeModifiable true;

adjustTimeStep  no;
maxCo           0.5;
```

As it can be seen, the `startTime`, `endTime`, `deltaT` and `writeInterval` entries are read from the `start`, `end`, `delta` and `write` variables respectively. Those variables are defined in the included dictionary `timeDict` as shown:

```
start          0;
end            1e-3;
delta          1e-5;
write          10;
#inputMode     merge
```

These sample values will be changed later on. This kind of file connection with the `#include` instruction is particularly useful when some parameters are going to be changed frequently, or in a lot of places at the same time, so that these changes can be quickly performed on a single file.

The `decomposeParDict` file can be kept from the `gearSnappy` case directory. The complexity of the case makes it a good idea to run the code in parallel. Also, this was one of the main justifications of this study: to be able to freely run the CFD solver in parallel with no worries for licensing restrictions.

The `fvSchemes` and `fvSolution` files can be directly copied from the `movingCone` tutorial, with the mentioned change of renaming the `cellMotionUx` entry to `cellMotionU` in the `fvSolution` file.

In the `fvSchemes` file the user is able to specify which numerical scheme is used for calculating time derivatives, gradients, divergences, laplacians and interpolations, among other things. On the other hand, as mentioned, in the `fvSolution` file the user specifies the different solvers that are going to be used to solve for the different variables, with their corresponding parameters such as relaxation factors. These two files are another glimpse at the power of customization OpenFOAM offers to the user.

After all the parameters have been set, the case is ready to run.

5.5.5 Running the Moving Gear

Before writing a script to automate the run process, it is interesting to run the case manually and check for all the possible problems that may arise. The first step to run the case manually is to decompose the domain the same way that was done with `snappyHexMesh`, by using the `decomposePar` tool. In theory this process poses no problem, but when trying to run the `pimpleDyMFoam` solver in parallel by typing:

```
foamJob -s -p pimpleDyMFoam
```

The following error is found, once per processor:

```
--> FOAM FATAL IO ERROR:
size 10270 is not equal to the given value of 2376

file:
/home/userName/Desktop/gearMain/gearMove/processor0/0/pointMotionU::
boundaryField::gear0 from line 46 to line 54.
```

By manually inspecting the `pointMotionU` file located inside one of the processor's `0` directory one finds that the `uniform` boundary conditions on gears has been substituted by a `nonuniform List<vector>` entry. If the write mode is set to `ascii` in the `controlDict` file, one can see that the `processor0/0/pointMotionU` shows:

```
    gear0
    {
        type            angularVelocity;
        axis            (0 0 1);
        origin          (0 0 0);
        angle0          0;
        omega           52.36;
        p0              nonuniform List<vector>
10270
(
(-0.0214975 -0.00630927 0)
[...]
)
```

But the list is incorrectly generated. This is because the `decomposePar` tool doesn't handle correctly the user-defined boundary conditions, as explained by José Plácido Parra Viol in [2]. Further examining the file one notes the following additional `processor` patches and boundary conditions, such as:

```
    procBoundary0to4
    {
        type            processor;
    }
```

These additional patches are created to keep the different processors connected. Additionally, some patches are specified as a list of `0` length, for example:

```
    outletPatch
    {
        type            fixedValue;
        value           nonuniform 0();
    }
```

This is because that patch is on a different processor or processors, so no value has to be applied to any point in that processor.

After inspecting the `pointMotionU` file of the `processor` directories it can be concluded that the problem might be solved by substituting the decomposed `pointMotionU` files with the original one inside the `0` directory. The badly defined `angularVelocity` boundary conditions would be fixed, and the patches with no points in a processor would not cause any problem if specified as `uniform`, since the problem is caused by specifying boundaries with incorrect point lists. A `uniform` boundary condition would not be applied to any point if the processor has no points in that patch.

However, in order to be able to replace the generated files with the original one, the boundary conditions for each `processor` patch would need to be manually created. Fortunately there is an easy way of creating a boundary condition definition for multiple, similarly-named patches in no time by using wildcards.

OpenFOAM uses what are called regular expressions. One can define such an expression by using strings enclosed in quotes "`...`". As explained in [5], the following wildcards are allowed, among others:

Card	Definition
`.`	Matches any character
`( )`	Groups a series of characters
`[ ]`	Denotes a set of character matches
`*`	Matches the preceding character 0 or more times
`+`	Matches the preceding character 1 or more times
`?`	Matches the preceding character 0 or 1 times
`|`	Denotes alternate possibilities (`OR`)
`$`	End of line
`^`	Beginning of line. Also a `NOT` if whithin `[ ]`.

Table 5.2: Examples of wildcards allowed in regular expressions.

Since one knows the naming pattern for the `processor` patches, the following entry can be added to the original `pointMotionU` file inside the `0` directory:

```
"procBoundary.*"
{
    type            processor;
}
```

This way the `processor` boundary type is applied to any patch whose name begins by `procBoundary` and is followed by any number of any characters, as specified by the dot followed by the star at the end of the regular expression.

With this addition to the `pointMotionU` file inside the `0` directory, it can now replace the corresponding files inside the `processor` directories. Now the `foamJob` command can be launched and the simulation starts. But the complete flow simulation requires a small time step, making the calculations longer. It is because of this that another command is will be used:

```
foamJob -s -p moveMesh
```

With the `moveMesh` command only the mesh movement is calculated; flow variables are not taken into account. This way the maximum acceptable deformation of the mesh can be determined quicker than with `pimpleDyMFoam`.

After running the simulation the domain must be reconstructed again. This can be done in this case by running the `reconstructPar` tool. But when trying to run it another problem appears:

```
Reconstructing point fields

    Reconstructing pointVectorFields

        pointMotionU
*** glibc detected *** reconstructPar: malloc(): memory corruption:
0x0000000006278f80 ***
```

The reconstruction of the `pointMotionU` file fails. But the problem can be easily solved by removing all the `pointMotionU` files from inside the `processor` directories after the simulation takes place, as they are no longer needed. The fields of interest are the pressure `p` and the velocity `U`. After removing them the `reconstructPar` command works without any error showing up.

5.5.6 runMove

As with the meshing, the instructions needed to run the case are gathered inside a single bash script, so that all the required steps can be performed with a single command. As shown in Figure 5.18 the `runMove` script is located inside the `gearMain` folder, along with the `runMesh` bash script.

The `runMesh` code is described next. First the OpenFOAM commands are loaded. The script moves to the `gearMove` directory and decomposes the domain. Then for each `processor` directory the `pointMotionU` file is copied to that directory, overwriting the file that was decomposed incorrectly. After that the mesh is renumbered, as during the

meshing procedure, although this step is not completely necessary. Finally all the `pointMotionU` files inside all the `processor` directories are removed, prior to reconstructing the mesh. After the mesh has been reconstructed the `processor` directories and the log file can be deleted.

So the `runMesh` bash script code is finally:

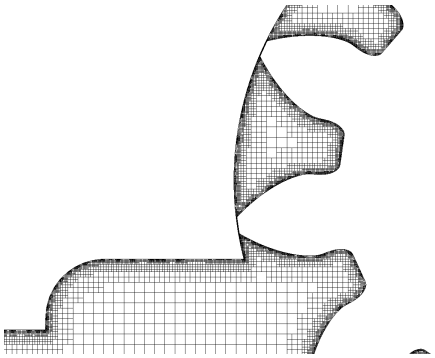
```
#!/bin/bash

. /opt/openfoam210/etc/bashrc

cd gearMove/

# Decompose and copy pointMotionU
decomposePar

for dir in $( ls | grep "processor" )
do
  cp 0/pointMotionU $dir/0/pointMotionU
done

# Run solver
foamJob -s -p renumberMesh -overwrite
foamJob -s -p moveMesh

# Delete all pointMotionU and Reconstruct
rm processor*/*/pointMotionU
reconstructPar
rm -rf log processor*
```

5.5.7 Testing the Limits of the Mesh

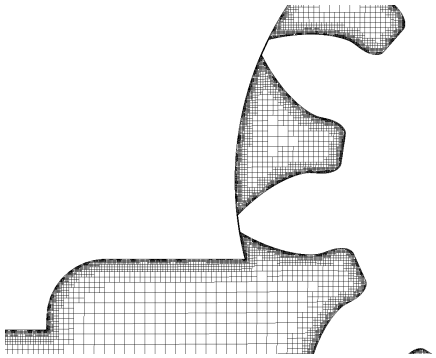
After running the above script and visually examining the results, which are shown on Figure 5.21, one can easily see that it is at the corners of the casing that the mesh is deformed the most, while the space between two consecutive teeth of the gears and the casing does not deform at all, since the points on the casing are allowed to slip while the gears rotate.

Also, the `checkMesh` utility can be used to check the different meshes for errors. Only three kinds of errors appear on the meshes, but their severity is increased with the rotation of the mesh as expected. Results are shown on Table 5.3.

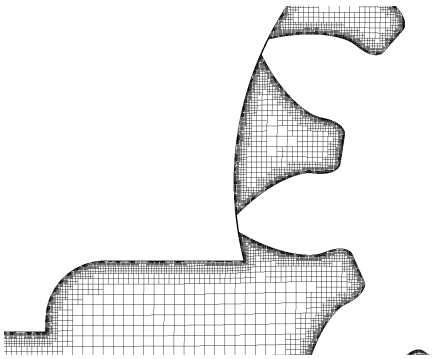
The limit to the number of errors in the mesh that one can allow to himself highly depends on the purpose of the calculations and the desired accuracy and precision. For this study, with the main purpose of developing methods and procedures to work with dynamic meshes, the limit is set to 0.0002 s, at least at this point, but for any other purpose the user will need to select a proper limit for his or her study.



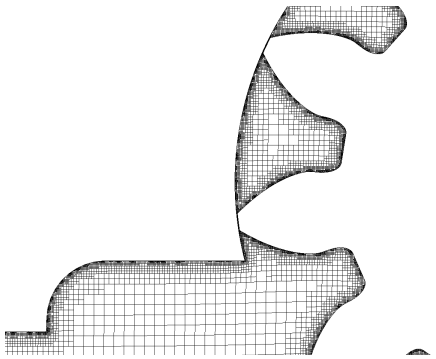
a) 0



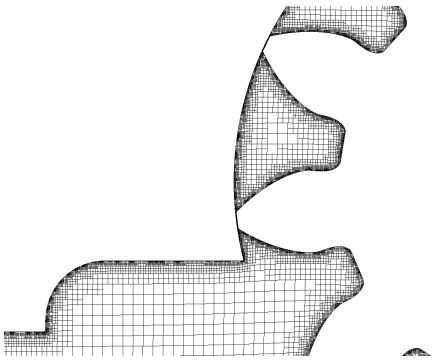
b) 0.0001



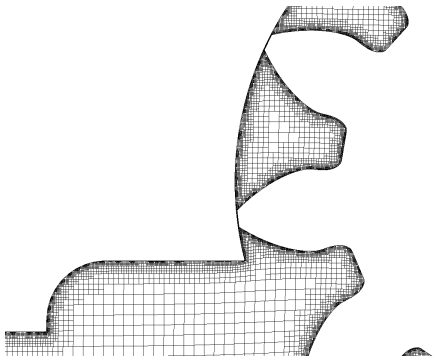
c) 0.0002



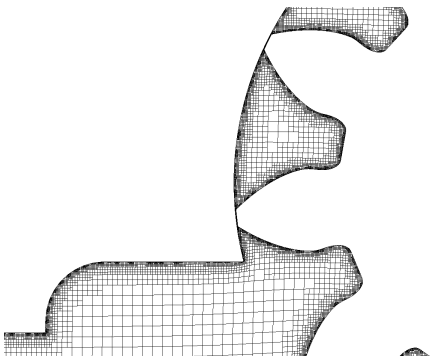
d) 0.0003



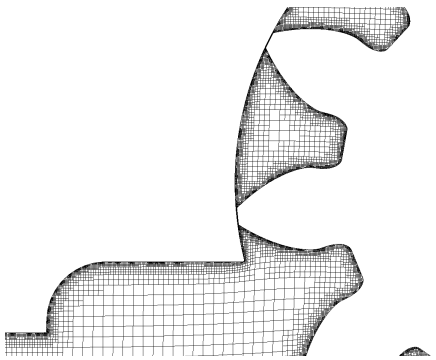
e) 0.0004



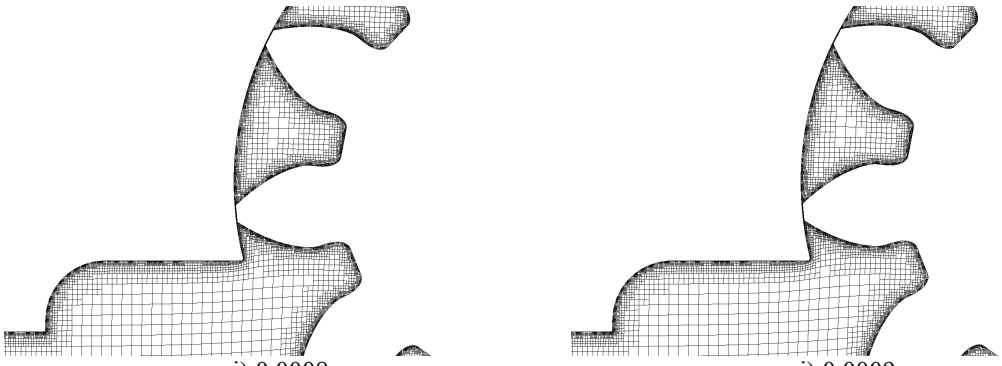
f) 0.0005



g) 0.0006



h) 0.0007



i) 0.0008 j) 0.0009

Figure 5.21: Deformation of the initial mesh with `moveMesh`.

Time (s)	Non-orthogonal faces	Incorrectly oriented faces	Highly skewed faces
0	0	0	1
0.0001	0	31	2
0.0002	5	27	7
0.0003	16	44	7
0.0004	34	64	15
0.0005	67	79	11
0.0006	136	142	18
0.0007	211	207	23
0.0008	372	307	44
0.0009	546	395	53
0.0010	772	479	74

Table 5.3: Results of the `checkMesh` tool for the deformed meshes.

5.6 Performing a Complete Gearing Cycle

Once the limit of the deformation has been determined it is time to move the mesh through a complete gearing cycle of the pump. The idea is to start with the initial mesh, deform it until the limit that has just been set, and then replace the mesh with a new one. This process can be repeated until a complete gearing cycle has been performed.

Indeed, after a gearing cycle the user will probably desire to perform another cycle, and so on, until the convergence criteria is met. Because of this, the different base meshes will be created firstly, and then the deformation and substitution will take place.

5.6.1 runAllMesh

In order to create the complete set of meshes with `snappyHexMesh`, a new bash script is created. Called `runAllMesh`, its mission is to properly set all the parameters required to generate a single mesh and launch the `runMesh` bash that was written in section 5.4.5 to automate the meshing process, and then repeat this for all the meshes that need to be created.

On Table 5.4 the basic parameters of the mesh generation and simulation are listed.

RPM	500
Angular velocity	52.36 rad/s
Number of teeth	11
Turn angle of a gearing cycle	0.5712 rad
Period of a gearing cycle	0.0109090 s
Maximum time between meshes	0.0002 s
Number of meshes beyond the first	54
Angle the last mesh must turn	0.005712 rad
Time the last mesh must turn	0.0000109 s

Table 5.4: Parameters for the dynamic meshes.

The code for the `runAllMesh` bash script is displayed below. In short description, the code loads a few variables and then iterates from `0` to `54`, calculating a new angle for the gears. Then it deletes the solids file read by the `points2stl` C++ program created in section 5.3, and writes a new one with this angle. After this the `points2stl` program is executed, and its output STL file is copied to the `gearSnappy` and `gearExtrude` directories to be used by `snappyHexMesh`. Next the `runMesh` script is launched, and once it ends the resulting mesh is stored inside a specific directory called `gearMeshes`, where all the `polyMesh` directories are saved inside directories named `0`, `1`, etc. up to `54`.

```
#!/bin/bash

pi=3.14159
rpm=500
dT=0.0002
nMeshes=54

mkdir ./gearMeshes

i=0

while [ $i -le $nMeshes ]
do
```

```
    #calculate angle
    angle=$(echo "scale=8; $i*$dT*($rpm*2*$pi)/60" | bc)

    #write a new solids file
    rm ./points2stl/solids
    echo "3 -1 11 " >> ./points2stl/solids
    echo "gear0 1913 0 0 $angle " >> ./points2stl/solids
    echo "gear1 1913 0 45.123 -$angle " >> ./points2stl/solids
    echo "case 1870 0 0 0" >> ./points2stl/solids

    #run points2stl
    cd points2stl
    ./points2stl
    cd ..

    #delete the old STL and copy the new one
    rm ./gearSnappy/constant/triSurface/triSurface.stl
    rm ./gearExtrude/constant/triSurface/triSurface.stl
    cp ./points2stl/triSurface.stl ./gearSnappy/constant/triSurface/
    cp ./points2stl/triSurface.stl ./gearExtrude/constant/triSurface/

    #mesh
    ./runMesh

    #store the mesh in ./gearMeshes
    mkdir ./gearMeshes/$i
    mv ./gearExtrude/constant/polyMesh ./gearMeshes/$i

    i=$(( $i+1 ))

done
```

Since it takes really long to create all 55 meshes (at about 15 minutes per mesh that's near 14 hours), and since this work is being done on a remote server via SSH connection, it is interesting to run the `runAllMesh` script in the background, so that the connection can be closed on purpose without the process stopping, and with no risk of it stopping in case of connection failure. It is interesting however to be able to see the output of the whole process at any time, even after a reconnection. In order to accomplish that the script is run with the following command:

```
./runAllMesh > logAllMesh &
```

This way all the output of running `./runAllMesh` is stored in the `logAllMesh` file (because of the `> logAllMesh`), and the process is run in the background (because of the ampersand `&`), so one can safely log out of the remote server and the script is kept running. The last lines of the `logAllMesh` file can be read with the command:

```
tail -f logAllMesh
```

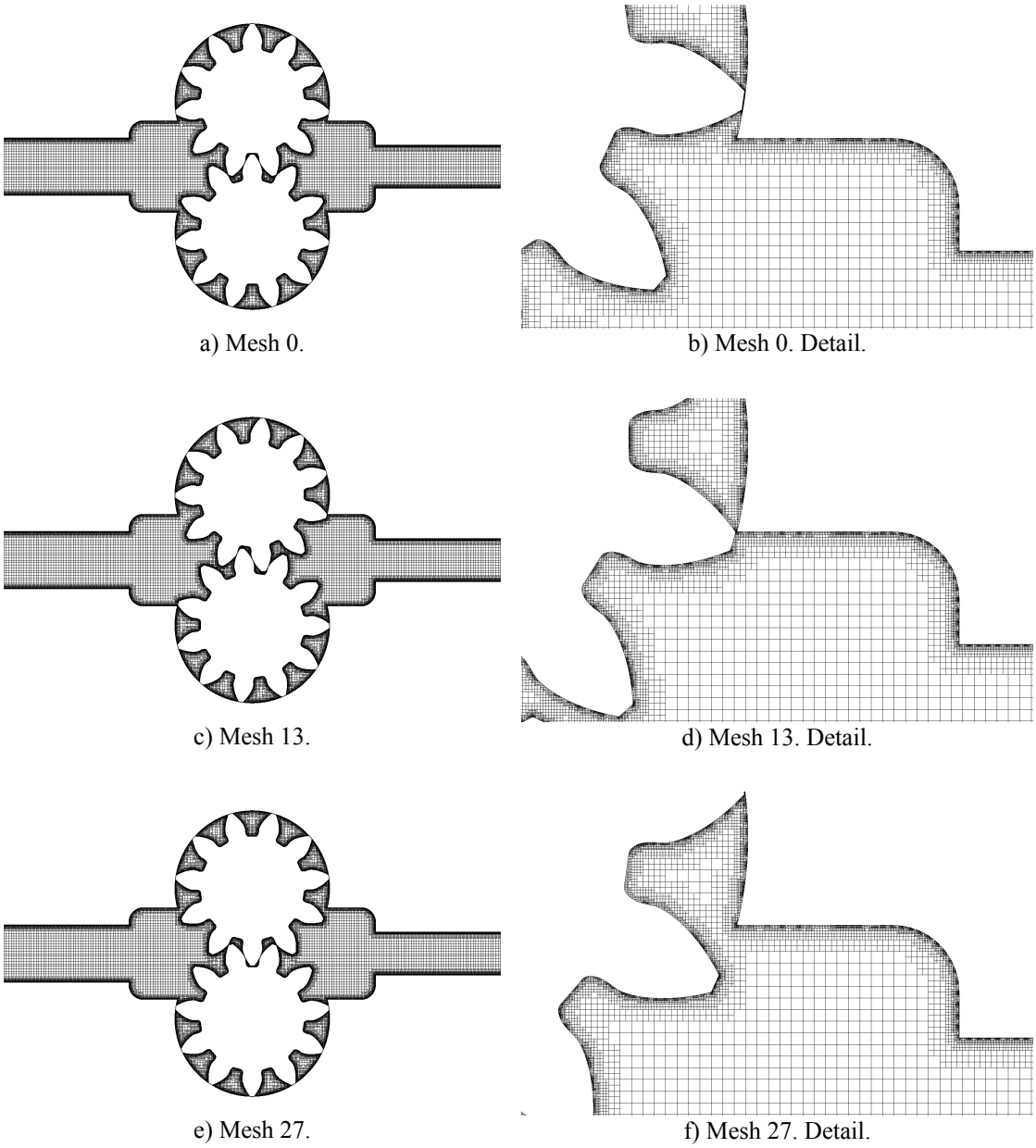
The `tail` program will display the last lines of the `logAllMesh` file, and will do so in a continuous way because of the `-f` option. To close it the Ctrl+C keyboard shortcut can

be used, it will kill most foreground running programs. But if the user wants to kill the running script, since it is running in the background, it must be killed with the `pkill` command:

```
pkill runAllMesh
```

This will kill the script, but not the last application run with it, which most of the time is `snappyHexMesh`, although this can be checked with the `top` utility. The running application must be killed separately.

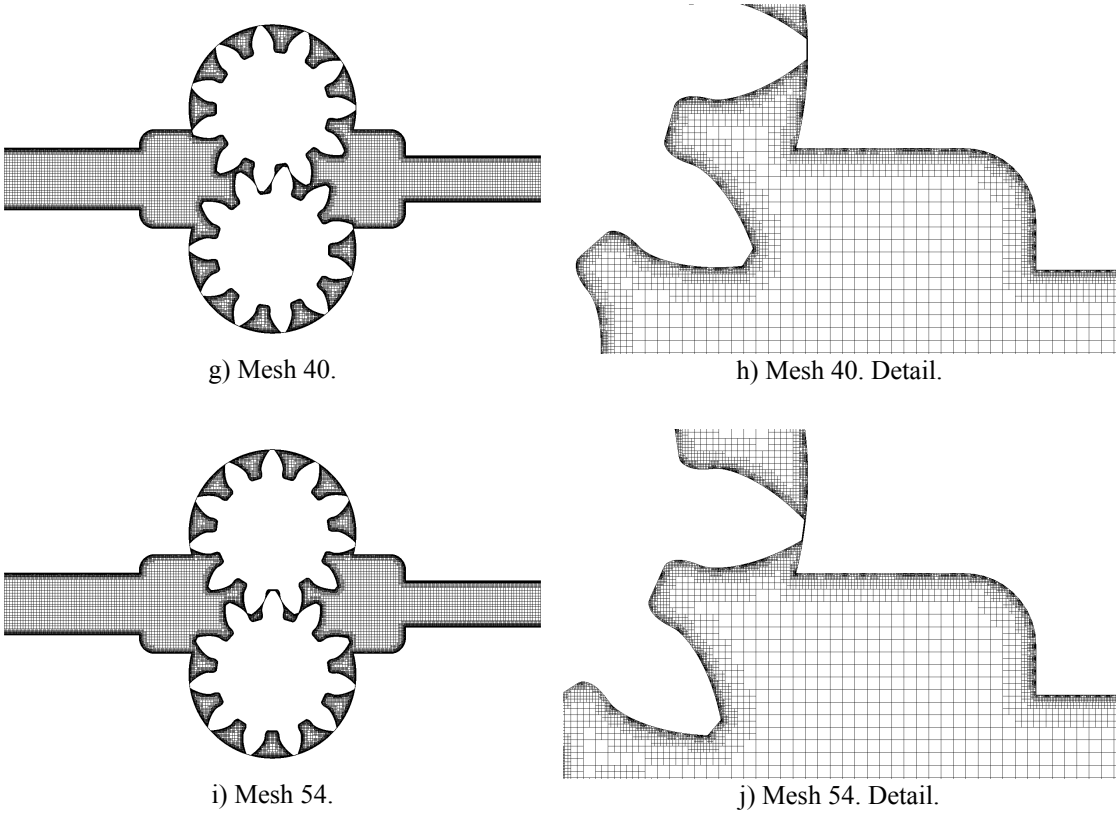
Some of the meshes created with the `runAllMesh` script are shown in Figure 5.22:



a) Mesh 0. b) Mesh 0. Detail.

c) Mesh 13. d) Mesh 13. Detail.

e) Mesh 27. f) Mesh 27. Detail.



g) Mesh 40. h) Mesh 40. Detail.

i) Mesh 54. j) Mesh 54. Detail.

Figure 5.22: Meshes generated with `runAllMesh`.

It has some interest to note that, since the same `blockMesh` background mesh and the same `snappyHexMesh` parameters are being used for all meshes, most points of the mesh do not change. It is said by David del Campo Sud in [1] that the simulation of cavitation was badly affected by interpolation errors produced each time the mesh was regenerated.

Although it could be very expensive in terms of time, in the future it could be studied if it is possible to run a simulation consisting of only generated meshes, without deforming the mesh. This way interpolation would be very localized, only very near the gears, and maybe cavitation simulations are not negatively affected.

5.6.2 runAllMove

After all the base meshes have been created with the help of the `runAllMesh` bash script, now another script is created, named `runAllMove`. Similarly to the `runAllMesh`, this script will perform a loop in which the parameters for the `runMove` script are set to their appropriate values for each iteration, an then the `runMove` script is run. After each iteration some representative meshes are stored.

```
#!/bin/bash

deltaT=2e-6
endTime=0.0002
writeSteps=25
endLast=.000108
writeLast=27
nMeshes=54
nCycles=1
mkdir gearResults

i=1
while [ $i -le $nCycles ]
do
  j=0
  while [ $j -le $nMeshes ]
  do
    cp -rf gearMoveCopy/* gearMove/
    cp -rf gearMeshes/$j/polyMesh/ gearMove/constant

    if [ $j != $nMeshes ]
    then
      rm gearMove/system/timeDict
      echo "start  0;" >> gearMove/system/timeDict
      echo "end    "$endTime";" >> gearMove/system/timeDict
      echo "delta  "$deltaT";" >> gearMove/system/timeDict
      echo "write  "$writeSteps";" >> gearMove/system/timeDict
      echo "#inputMode merge" >> gearMove/system/timeDict
    elif [ $j = $nMeshes ]
    then
      rm gearMove/system/timeDict
      echo "start  0;" >> gearMove/system/timeDict
      echo "end    "$endLast";" >> gearMove/system/timeDict
      echo "delta  "$deltaT";" >> gearMove/system/timeDict
      echo "write  "$writeLast";" >> gearMove/system/timeDict
      echo "#inputMode merge" >> gearMove/system/timeDict
    fi

    ./runMove

    if [ $i = $nCycles ]
    then
      rm -rf gearMove/{0,constant,system,log}
      if [ $j != $nMeshes ]
      then
        cp -rf gearMove/5e-05 gearResults/$j.1
        cp -rf gearMove/0.0001 gearResults/$j.2
        cp -rf gearMove/0.00015 gearResults/$j.3
        cp -rf gearMove/0.0002 gearResults/$j.4
      else
        cp -rf gearMove/5.4e-05 gearResults/$j.1
        cp -rf gearMove/0.000108 gearResults/$j.2
      fi
      rm -rf gearMove/*
    fi

    j=$(( $j+1 ))
  done
  i=$(( $i+1 ))
done
```

Before the script is run a copy of all the contents of the `gearMove` directory are stored in a backup copy at `gearMoveCopy`. Then, when each iteration starts, the `gearMove` directory is cleared and the backup is restored, so that each `runMove` starts with a clean configuration.

Note how the parameters that are stored in the `timeDict` file change for the last mesh iteration, according with Table 5.4. Also, the meshes are stored somehow manually, since the names of the folders to be copied are hard coded in the script.

It is important to keep in mind that all the simulations must begin at time 0 s, otherwise the gears would rotate to match their position with the starting time. For instance, if the second iteration were to start at time 1 s, the mesh would rotate 52.36 rad before that simulation ever begins, rolling the mesh around both gears and rendering it completely unusable.

After running the `runAllMove` script the results are quite satisfactory. Results can be seen in the animations that are in the media given with this work.

5.6.3 runPimple & runAllPimple

It must be noted too that the above script is conceived for moving the mesh exclusively, with the `moveMesh` command no flow is being calculated. The `runAllMove` script does consider an important point for a flow simulation, since it is able to run for multiple gearing cycles before writing the results of the last one. But to be able to simulate the complete flow a last step is needed: the flow results must be interpolated from one mesh to the next one.

In the first place, the `runMove` script can be quickly modified to execute the `pimpleDyMFoam` application instead of the `moveMesh` application. With that easy change the new script can be saved as `runPimple`.

Next the `runAllMove` bash script is copied as `runAllPimple`, since the base of the script will be the same. After that, the `mapFields` utility must be added to the `runAllPimple` script. This utility is explained in the `cavity` tutorial presented in [3]. In short, it requires the user to specify the source case from which the results are going to be interpolated. The fields from the starting time specified in the `controlDict` of the target case are mapped onto it.

However, the nature of the gear pump case makes it difficult to run a full flow simulation at this point. For instance, in a real pump only one of the gears, the driver gear, is powered by an engine, and the other one, the driven gear, rotates because of the contact between the two of them.

But no contact can exist between the gears in the CFD mesh. This was solved by David del Campo Sud in [1] by locating the theoretical contact point during the simulation (done with ANSYS Fluent in that case) and modifying the viscosity at that point. By greatly increasing it the cell became effectively a virtual contact point that allowed a correct simulation of the flow.

But this application is far beyond the scope of this study, so it is not developed here. However, if one tries to run the simulation of the gear pump with `pimpleDyMFoam`, one finds that the difference in pressure between the inlet and the outlet increases rapidly as it can be seen in Figure 5.23. This causes a relatively high speed flow at the gearing zone, where the mesh is most refined, as depicted in Figure 5.24. Because of this the required time step is very small, and even when using time steps that would not allow the simulation to finish in a reasonable amount of time, the solution explodes.

It is because of this that the interpolations cannot be tested with the gear pump case, and a new test case is developed. This test case consists basically on a copy of the `gearMain` case. Differences are listed below:

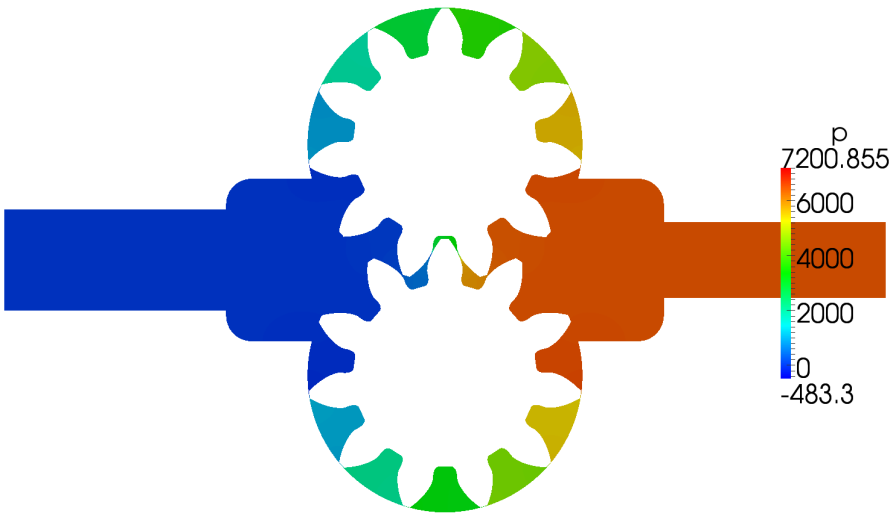


Figure 5.23: The difference in pressure rapidly builds up.

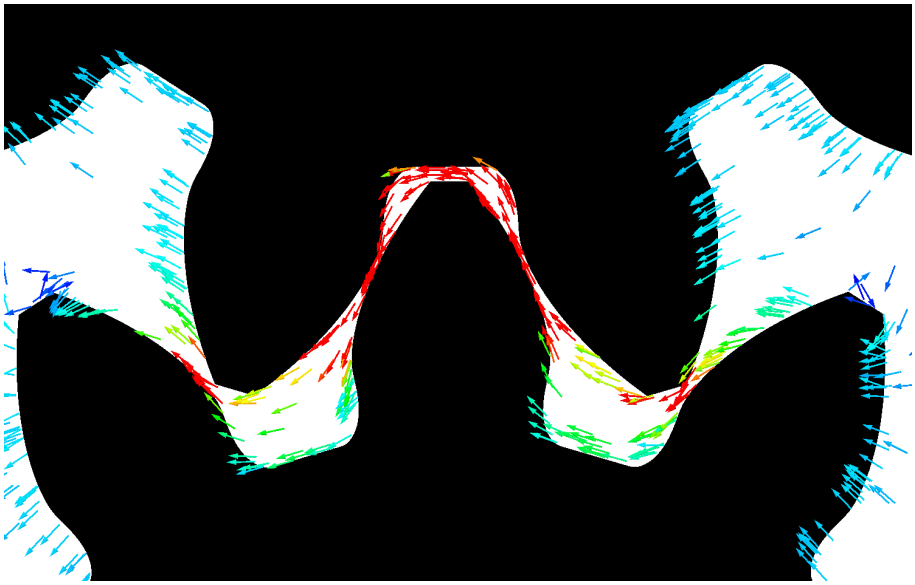


Figure 5.24: High speed flow at the gearing zone.

- Instead of using three solids for the two gears and the casing, a single solid, representing a cross, is used. The point list can be easily created manually. The cross has beams 2 mm wide and a total span of 8 mm.
- The background mesh has been reduced to a 10 mm per 10 mm square with 50 cells in each direction.
- The refinement in `snappyHexMesh` has been reduced to `(2 3)`.
- 10 meshes are created, the initial one and 9 more beyond that.
- Boundary conditions are the same that for the square in Figure 5.20: open ends on right and left (no pressure neither velocity gradient), walls on top and bottom (no pressure gradient, zero velocity). Angular velocity is fixed to 15 RPM.

All meshes must cover the same time gap of 0.1 s for them to cover a quarter of a revolution in total, in 1 s. This simplifies the `runAllPimple` bash script, as no different consideration has to be given to the last mesh. The `runAllPimple` script including interpolation for this case is shown on the next page.

It can be seen that, for interpolation, a new directory called `gearMovePrevious` has been created. Although no gear is being used the name of the directories are not changed for the sake of simplicity. That directory must contain the last time directory of the last run, as well as its initial `constant/polyMesh` directory, before results can be mapped.

```
#!/bin/bash

deltaT=0.00004
endTime=0.1
writeSteps=1250
nMeshes=9
nCycles=5
mkdir gearResults

i=1
while [ $i -le $nCycles ]
do
  j=0
  while [ $j -le $nMeshes ]
  do
    rm -rf gearMove/*
    cp -rf gearMoveCopy/* gearMove/
    cp -rf gearMeshes/$j/polyMesh/ gearMove/constant

    rm gearMove/system/timeDict
    echo "start  0;" >> gearMove/system/timeDict
    echo "end    "$endTime";" >> gearMove/system/timeDict
    echo "delta  "$deltaT";" >> gearMove/system/timeDict
    echo "write  "$writeSteps";" >> gearMove/system/timeDict
    echo "#inputMode merge" >> gearMove/system/timeDict

    if [ $j = 0 ] && [ $i = 1 ]
    then
      cd . #do not interpolate on first run
    else
      cd gearMove
      mapFields ../gearMovePrevious -sourceTime latestTime
      cd ..
      cp -rf gearMoveCopy/0/pointMotionU gearMove/0/pointMotionU
    fi

    ./runPimple

    mkdir gearMovePrevious/0
    rm -rf gearMovePrevious/0/*
    rm -rf gearMovePrevious/constant/polyMesh/*

    cp -rf gearMove/0.1/* gearMovePrevious/0/
cp -rf gearMove/constant/polyMesh/* gearMovePrevious/constant/polyMesh

    if [ $i = $nCycles ]
    then
      rm -rf gearMove/{constant,system,log}

      cp -rf gearMove/0 gearResults/$j
      cp -rf gearMove/0.05 gearResults/$j.1
      cp -rf gearMove/0.1 gearResults/$j.2

      rm -rf gearMove/*
    fi

    j=$(( $j+1 ))
  done
  i=$(( $i+1 ))
done
```

As it can be seen on the code, after writing the `timeDict` file the `mapFields` utility is run (the `-sourceTime latestTime` option probably is not needed, but it was left there anyways). Both the last time directory and the `constant/polyMesh` directory are copied to the `gearMovePrevious` directory just after the `runPimple` bash script ends. Next, if the script is in the last of the cycles, it saves the results to the `gearResults` directory.

The use of the `mapFields` utility requires a `system/mapFieldsDict` file inside the `gearMoveCopy` directory. This file would not be required if the `mapFields` had worked with the `-consistent` option, but for an unknown reason it didn't. Anyways, the only two entries this dictionary must have are left empty:

```
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      mapFieldsDict;
}

patchMap ( );
cuttingPatches ( );
```

An explanation for these entries can be found in [3]. After the `runAllPimple` script ends the results of the 5th quarter-revolution cycle can be examined. It is difficult to appreciate it in paper, but in Figure 5.25 one can observe that the results before and after the interpolation are a bit different. This can be seen better with a computer by alternating the images.

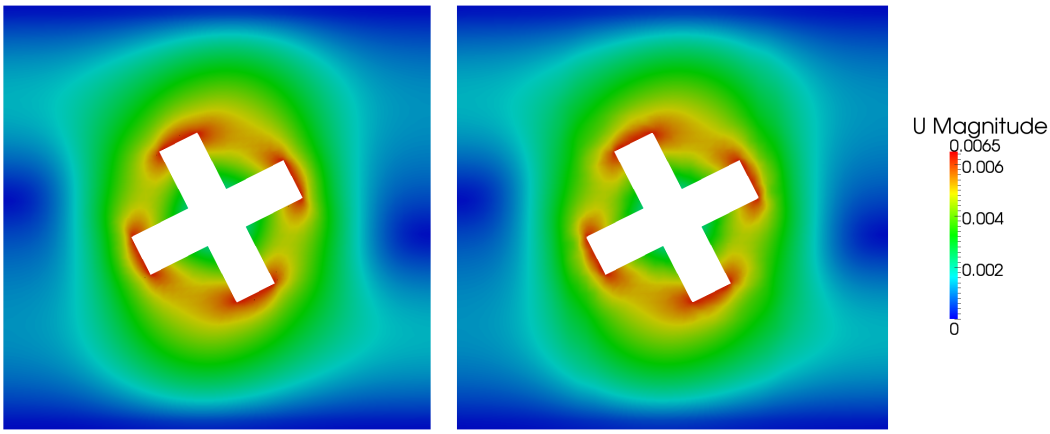


Figure 5.25: Results for t = 0.3 s before (right) and after (left) the interpolation.

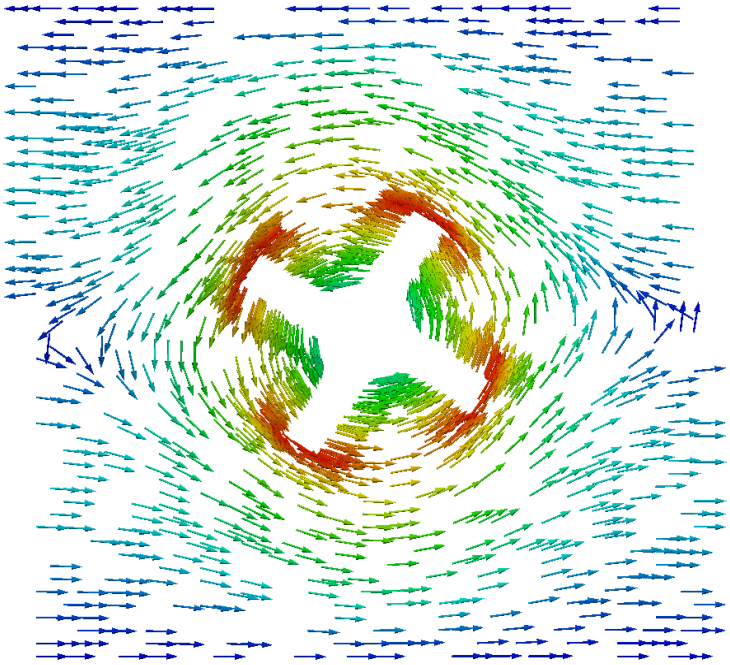


Figure 5.26: Results for t = 0.6 s before the interpolation.

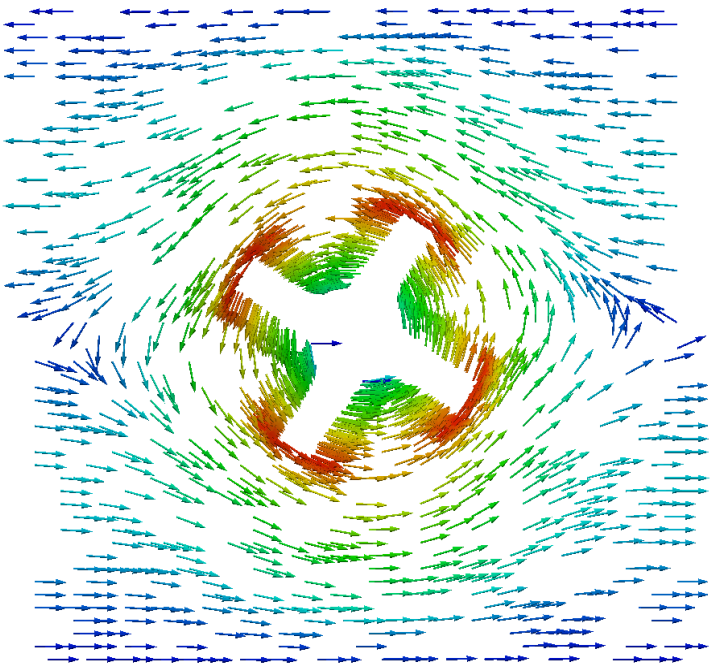


Figure 5.27: Results for t = 0.6 s after the interpolation.

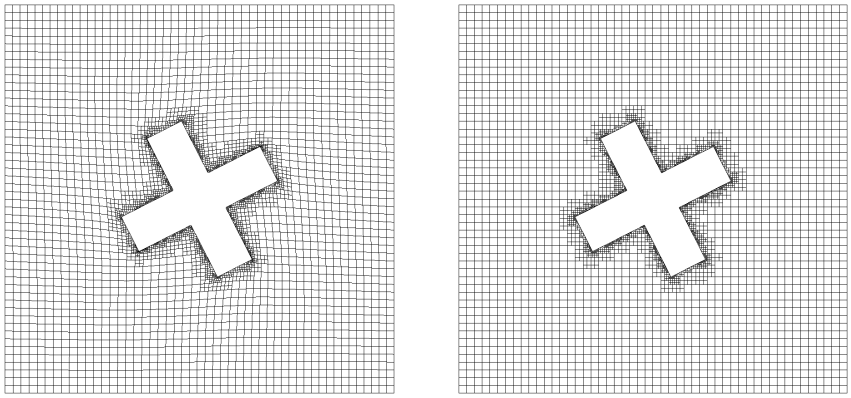


Figure 5.28: Deformed (right) and regenerated (left) meshes for $t = 0.3$ s.

This difference on the results before and after the interpolation are more visible on Figure 5.26 when compared with Figure 5.27, where a pair of horizontal, no-velocity arrows have appeared in the rotating cross wall. This can be due to interpolation failing in a few points, at which the initial value of velocity has been left. Also, it can be seen in Figure 5.28 the regeneration of the mesh.

In overall, the results of the `runAllPimple` script are satisfactory. It must be remembered, though, that the interpolation errors where crucial when dealing with cavitation simulations. But, nevertheless, the main purpose of this study is not to study cavitation, but to provide a procedure to work with dynamic meshes in OpenFOAM.

6 RESULTS AND CONCLUSIONS

6.1 Results of This Study

The complete procedure developed in the previous section is qualitatively summarized here, step by step:

1. A geometry for the gears and the casing has been obtained, in the form of a list of points, from a provided Gambit MSH file. This geometry can be obtained from other sources, but the target stays the same: to obtain a separate list of points for each boundary of the gear pump domain, or for any other problem the user may wish to solve.
2. A C++ program has been developed to convert a group of solids, defined by lists of two-dimensional points, to an STL surface. Again, this STL surface can be obtained with other methods, typically any CAD software is able to export to this format, but the point here is that the C++ program developed here is able to quickly modify the geometry in an automated way, as it is done in this study with the rotation of the gears.
3. The parameters for meshing the obtained STL surface with `snappyHexMesh` in parallel have been determined, and a script to automatically obtain a single mesh has been written. The quality of the obtained mesh depends highly on these parameters, as well as the time required to generate them. A balance must be found, specially for the refinement values. Also, the procedure to finally obtain a single, two-dimensional mesh required multiple steps to be performed. In short these steps were refinement, extrusion and snapping.
4. The parameters for moving and deforming the mesh have been studied, and a script to automatically move the mesh has been written. In particular, a new boundary condition had to be implemented into OpenFOAM.
5. The maximum time of deformation before a mesh should be regenerated has been determined. This is an important analysis, the user must know how many deformation he or she can afford before a new mesh has to be used. This analysis depends highly on the kind of situation that is going to be simulated.

6. A script has been written to automatically create as many meshes as were needed. With the maximum deformation obtained in the previous step one can know how many meshes will be needed to perform the whole simulation. It is interesting to generate all the meshes at once, specially in the case of the gear pump and other rotatory dynamic meshes, where multiple rotation cycles are going to be simulated. In these cases the meshes need to be generated first, and then are stored for later use on each cycle over and over, until the simulation ends.
7. Another script has been written to automatically move the mesh up to the previously determined maximum time, substitute it with a new mesh, and continue the movement to complete the gearing cycle, moving the mesh only, without flow calculations. This was done in order to check how the mesh moved and regenerated quicker than it would have been if the flow had been calculated directly. Once the mesh moves and regenerates adequately the step of the flow simulation can start to be analyzed.
8. The procedure to be able to interpolate the results from a mesh onto another one has been studied. Interpolation is needed to obtain continuity in the simulation, being able to port the results from a mesh that has reached the deformation limit to the next new mesh.
9. A final script has been developed to perform the simulation of the flow, automatically changing the deformed mesh with a new one, and interpolating the results each time the mesh reached its maximum allowed deformation. The simulation is run for as many rotation cycles as the user wishes, the results of the last rotation cycle are saved (although this, like any other code in this work, can be changed if the user finds it appropriate). This last script was tested with a different case due to difficulties to adequately run the gear pump simulation, but should these difficulties be solved, the developed script would be able to run the simulation of the gear pump with little or no modification.

This procedure that has been developed in this study and is here summarized is the main result of this work, and the author wishes to contribute with it to the OpenFOAM community, where probably someone will find it useful for another work.

6.2 Conclusions and Other Considerations

From the development of this work some remarks and conclusions arose, they are listed next:

- OpenFOAM in general, and `snappyHexMesh` in particular, work with three-dimensional domains. To perform a two-dimensional simulation one needs a one-cell thick mesh, with empty front and back patches. But since `snappyHexMesh` refines in the third dimension too, the generated mesh cannot be used for a two-dimensional simulation. It is because of this that a patch of that mesh has to be extruded with a one-cell thickness to be of use for this study.
- In case the gear pump simulation was to be three-dimensional, the mesh obtained with `snappyHexMesh` could be used. But probably it could be interesting to extrude the mesh anyways, in order to have a uniform number of cells in the third dimension, and even using the `expansionRatio` option of the `extrudeMeshDict` file to create a more dense mesh near a side wall. In this case a `symmetryPlane` boundary condition could be used at the other side wall.
- During the development of the extrusion of the mesh it has been stated that the `extrudeMesh` tool can generate OpenFOAM meshes from flat STL meshed surfaces. This can be interesting to import meshes from other programs (although OpenFOAM counts with a large number of mesh importers), or for someone to create a meshing tool that saves its output to STL.
- Running `snappyHexMesh` in parallel is very sensitive to hardware configuration, software configuration and possible memory corruption or miscommunication between processors. It was observed that exactly the same meshing process with the same parameters was completed without any hassles in one machine, whereas the process always ended abruptly after some time after being started on another machine. This behavior was not observed when other applications, such as `moveMesh`, were run in parallel.
- While the user-defined boundary condition was coded, one could see how powerful OpenFOAM is in terms of potential: being open-sourced allows anyone to check the code and to customize the program with new functionalities.

- While, because of the movement of the gears, the mesh gets greatly distorted at the corners of the case where the housing of the gears end, at the rest of the domain the mesh adapts quite well. If the mesh could be forced somehow to stay still near those points, the allowed rotation of the gears until a new mesh is required could be increased. This would not have a large effect however, since at some near time the gearing zone will be affected of high deformation too. Also, since new meshes are stored for multiple cycles since before the simulation starts, their cost in time is not that high.
- Finally, the fact that the final simulation was performed with a different test case proves how easy it is to modify the scripts presented with this work for other geometries and problems, which surely makes them more valuable for the OpenFOAM community.

This work has originated some personal thoughts and feelings too:

- In a time where every computer program has a graphical user interface (GUI) so that users find it more friendly and intuitive, the author of this study had to work most of the time with a command-line interface (CLI) from a terminal, connected to a server via a Secure Shell (SSH) connection. Although nowadays many people would find this discouraging, it was actually fast, effective, and even amusing at some points. Every day a new trick was discovered, a command was learned, or a mistake was committed. In overall the author feels that the CLI is an extremely powerful tool. This doesn't mean that GUIs are not needed, they make computers accessible for most people, and probably more human.
- Also, the fact that this work has been done entirely with open source software makes one think about the amount of money a business, for instance, could save in software licenses if its computers were based on open source software. The budget of the next section could have probably gone anywhere from double (if using commercial operating systems or other general software) to tens of times (if using commercial CFD tools) the total cost of this study (depending on the amount of software purchased). It must be noted, however, that open source software often has no warranty, but this is no different from a program that is written for self use, such as the `points2stl` C++ program written for this work.

6.3 Future Work

This work represents only another small step, after the work done by José Plácido Parra Viol in [2], towards the end target of performing the simulations done by David del Campo Sud in [1] with OpenFOAM, so that they can be run in parallel with no licensing cost, allowing for more complex simulations. Many more steps need to be done in that direction, some of them are listed next:

- Developing a method to simulate the contact point between the gears in OpenFOAM, in order to obtain a relatively accurate solution of the flow (relatively if one accounts for the fact that a two-dimensional simulation is being done). This could be done in several ways, it should be studied which one could be implemented into OpenFOAM, how it could be implemented, and how effective it is. As it was done by David del Campo Sud in [1], the viscosity at the contact point between the gears could be heavily increased to disallow the flow through it. Some ideas are presented of how this could be done:

  a) By defining the viscosity as a function that increases greatly with the velocity or when near a wall.

  b) By modifying the solver so that at the contact point it modifies the viscosity of the fluid.

- Since there are hydraulic forces that act on the gears, those move a little bit from their center as their rotate. It could be interesting to calculate the direction of those forces, and to add another "viscosity generated" contact point between the gears and the casing at the point those forces move the gears to.

- Performing a three-dimensional simulation of the gear pump, either by extruding a multiple-cells thick mesh or by directly generating a three-dimensional mesh. The later has the ability to reproduce more accurately the joining of the inlet and outlet pipes with the chamber of the pump, as those pipes are cylindrical but in a two-dimensional mesh they are treated as being rectangular, and that generates errors in the velocity field at those zones. A three-dimensional simulation could also include boundary layer effects on the sides of the casing, and turbulence modeling could be done in the third dimension too.

- Furthermore, after this three-dimensional simulations were up and running, the mesh could be made more complex by adding the features of a real pump, such as the empty spaces between the sides of the casing and the gears, or the grooves and sealing rings the sides of the casing have. But these simulations are still quite far from now, though.
- Being able to simulate cavitation in OpenFOAM is an important step towards the ultimate target too. Also, it is important to check the effect of interpolations between the deformed meshes and the new ones on the simulation of cavitation, and studying if a method to simulate the flow using only new, generated meshes with no deformation could be implemented in order to reduce interpolation errors.
- Studying ways of allowing more rotation between mesh regenerations, such as using some sort of sliding interfaces to avoid the mesh degeneration at the corners of the housing of the gears.

Additionally, more steps forward could be done in the field of OpenFOAM meshing and dynamic mesh simulation. Some of them could be:

- Studying other procedures to create two-dimensional meshes. Although the procedure developed here with `snappyHexMesh` is considered to be quite good in terms of time, mesh quality and automation of the process, it would be interesting to compare it to other meshers.
- Modifying `snappyHexMesh` to work with two-dimensional meshes. Although, in general, hexahedral meshes created with `snappyHexMesh` have a good quality, the fact it is refining the cells in the z direction makes the process slower than it could be if cells were refined only in the x and y directions. This would require a huge knowledge of how OpenFOAM and `snappyHexMesh` are coded.
- Working with meshes that are modified in a way depending on the solution itself, such as in aeroelasticity simulations.
- Porting the scripts here presented to a three-dimensional, more general problem configuration.

7 BUDGET

The cost of this study is detailed in the tables below.

7.1 Work Hours

The hourly rate has been fixed at 16 €/h.

Concept	**Time**	**Cost**
Learning SSH Remote CLI	2 h	32 €
Updating Ubuntu in AeroCluster	2 h	32 €
Installing OpenFOAM in AeroCluster	2 h	32 €
Dynamic Mesh in OpenFOAM Research	13 h	208 €
Gear Pump Simulation Research	19 h	304 €
Custom Boundary Condition – Research	2 h	32 €
Custom Boundary Condition – Development	2 h	32 €
Cavity with Obstacle – Testing	15 h	240 €
Importing Geometry	3 h	48 €
`points2stl` Programming	10 h	160 €
`points2stl` Testing	19 h	304 €
`snappyHexMesh` – Research	20 h	320 €
`snappyHexMesh` – Initial Development	41 h	656 €
`snappyHexMesh` – Parameter Optimization	43 h	688 €
`snappyHexMesh` – Debugging	65 h	1040 €
`moveMesh` – Initial Development	28 h	448 €
`moveMesh` – Parameter Optimization	26 h	416 €
`moveMesh` – Debugging	9 h	144 €
`mapFields` – Initial Development	2 h	32 €
`mapFields` – Debugging	6 h	96 €
Bash Scripting	10 h	160 €
Document Writing	67 h	1072 €
Subtotal	**406 h**	**6496 €**

Table 7.1: Detailed budget for the work hours.

7.2 Hardware Infrastructure

Concept	**Units**	**Cost**
ClusterAero Computers and Setup	5	4000 €
Subtotal		**4000 €**

Table 7.2: Detailed budget for the hardware infrastructure.

7.3 Software Licenses

Concept	**Units**	**Cost**
Ubuntu 10.10	5	0 €
Ubuntu 11.10	1	0 €
Ubuntu 12.04	1	0 €
OpenFOAM 2.1.0	6	0 €
GNU Compiler Collection 4.6	2	0 €
LibreOffice 3.4.4	1	0 €
LyX Document Processor 2.0.0	2	0 €
GIMP Image Editor 2.6	1	0 €
Inkscape 0.48	1	0 €
OpenShot Video Editor 1.2	1	0 €
Highlight 3.5.2	1	0 €
Subtotal		**0 €**

Table 7.3: Detailed budget for the software licenses.

7.4 Total

Concept	**Cost**
Work Hours	6496 €
Hardware Infrastructure	4000 €
Software Licenses	0 €
Total	**10496 €**

Table 7.4: Total budget.

8 ENVIRONMENTAL EFFECTS

This study has been entirely computer-based. No residuals were generated during this work, except from the production of the energy consumed by the computers used, the computers themselves the day they will be dismantled, and any printed copy or physical media used to distribute the work.

As such, the only environmental concerns this study arises are to ensure a rational use of energy, and to properly recycle both the computers and the physical paper or media should them one day be destroyed.

By following these recommendations the environmental footprint of this study can be safely considered insignificant, and far below the legal requirements.

9 REFERENCES

[1] DAVID DEL CAMPO SUD. *Analysis of the Suction Chamber of External Gear Pumps and their Influence on Cavitation and Volumetric Efficiency* . A thesis submitted to the Universitat Politècnica de Catalunya for the degree of Doctor of Philosophy in the Escola Tècnica Superior d'Enginyeries Industrial i Aeronàutica de Terrassa, directed by ESTEBAN CODINA MACIÀ and ROBERTO CASTILLA LÓPEZ. March 2012.

[2] JOSÉ PLÁCIDO PARRA VIOL. *Estudio e implementación de nuevas funcionalidades de deformación de malla en un software de mecánica de fluidos computacional* . Final Project directed by ROBERTO CASTILLA LÓPEZ and DAVID DEL CAMPO SUD. June 2011.

[3] *OpenFOAM User Guide*. Online resource. January-June 2012. Available at:

http://www.openfoam.org/docs/user/

[4] *OpenFOAM Features Guide.* Online resoruce. January-June 2012. Available at:

http://www.openfoam.com/features/

[5] *OpenFOAM Advanced Training.* Guide for an OpenFOAM version 1.6 course. October 2009.

[6] HRVOJE JASAK, HENRIK RUSCHE . *Dynamic Mesh Handling in OpenFOAM*. Fourth OpenFOAM Workshop, Montreal, Canada, June 2009.